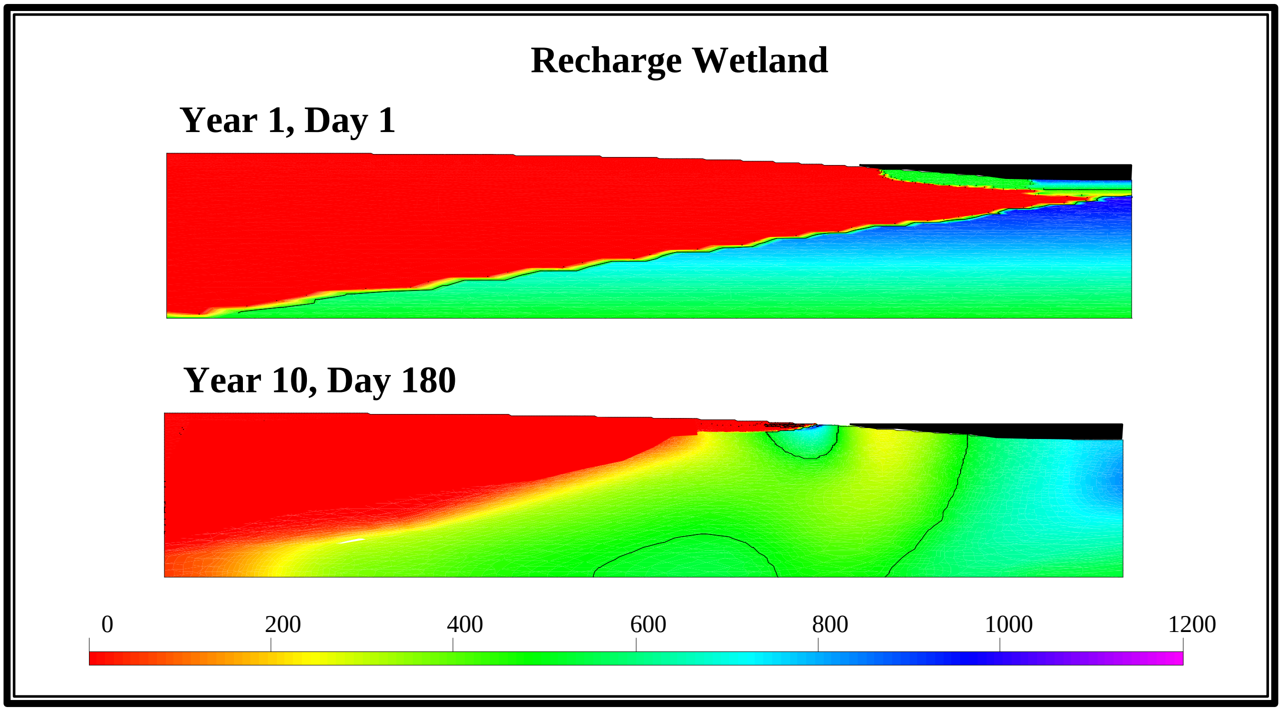
Modeling Soil Salinization Processes in Wetlands of the Upper Basin of Devils Lake and in Floodplain Soils along the Sheyenne River, with an Emphasis on the Effects of Alternatives Proposed to Reduce Devils Lake Flooding



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EXECUTIVE SUMMARY

The effects of hydrologic alterations on soil salinity are assessed through Hydrus 2D and UNSATCHEM computer modeling simulations of salinization processes in specific hydrogeologic settings. Hydrus 2D simulations were developed for drained and undrained wetlands in both recharge and discharge hydrologic settings in the Upper Basin of Devils Lake, and in riparian floodplain soils along the Sheyenne River as appropriate to the alternatives proposed to reduce Devils Lake flooding. UNSATCHEM column leaching simulations of the effects of gypsum on soil salinization processes were run on a typical loam and a typical clay loam soil.

While such modeling efforts illustrate for comparative purposes the general principles and mechanisms of soil salinization associated with the alternatives, they were not developed for predictive purposes. The principles illustrated in the simulations can be used as a general "guide" in conjunction with previous reports on salinization hazards associated with the alternatives to select drained wetland candidates whose restoration under the Upper Basin Storage alternative will have a minimal salinization effect on adjacent agricultural soils, and to identify areas along the Sheyenne River that may have salinization problems under the constructed outlet alternatives.

Simulation of Salinization Processes Associated with Wetland Soils in the Upper Basin

The following conclusions are drawn from the simulations of soil salinization in restored recharge and discharge wetlands.

1. A soil salinity hazard requires the presence of high levels of salts near the soil surface. In the absence of such accumulations, the restoration of recharge wetlands has a little risk of soil salinization. Minor edge-focused salinization typical of that found under natural conditions was observed in simulation, but not to levels that would result in substantive crop yield reductions.

2. Drained discharge wetlands typically have substantial amounts of subsoil salts that constitute a salinization risk upon restoration. Salts can be mobilized to the surface by increasing the elevation of water tables adjacent to the restored wetland. Salts can also preferentially be transported along sand lenses that can act as a conduit for water flow from the restored wetland. Relatively rapid salinization to levels that could reduce crop yields can occur under these circumstances.

Simulation of Salinization Processes in Sheyenne River Floodplain Soils

The following conclusions are drawn from the simulations of soil salinization in Sheyenne River floodplain soils.

1. Poorly and very poorly drained soils on the floodplain of the Sheyenne River accumulate salts because upward unsaturated groundwater-flow accumulates salts at the surface as evapotranspiration removes pure water. Salinization is greatest in low positions where

the water table is above a “critical depth.” Salinization of surface soils becomes progressively less as the depth to the water table increases.

2. In soils with low hydraulic conductivity (e.g. clay loam) the removal of water by evapotranspiration can exceed replacement by groundwater flow from the river, resulting in a groundwater depression during summer where the water levels in floodplain soils distant from the river are lower than the river stage.

3. Increasing the stage and salinity of the Sheyenne River can result in additional salinization of soils adjacent to the river. However, the data indicate that the increased salinization will be primarily confined to soils immediately adjacent to the river when those soils have characteristic, low hydraulic conductivity. Data from county soil surveys suggests that coarse textured soils are relatively rare on the floodplain of the Sheyenne River.

4. While groundwater intrusion is limited to areas immediately adjacent to the river, increased flooding under the outlet alternatives in shallowly entrenched areas above Lake Ashtabula especially could result in a salinization hazard induced by regular flooding persistently raising water tables.

5. Increased salinization of moderately well-drained floodplain soils on the elevated floodplains above the entrenched Sheyenne River downstream of Baldhill Dam is unlikely because the water tables would be well below the critical depth required for soil salinization.

The Effects of Gypsum on Soil Salinization Processes

Most saline soils in North Dakota contain gypsum to greater or lesser degrees. The presence of gypsum can increase the salinization hazard of soils subjected to salt mobilization because calcium ions released as gypsum dissolves are preferentially adsorbed on soil colloids, replacing exchangeable magnesium and sodium which then add to the salt load in the groundwater. Under these circumstances the exchange complex, consisting of positively charged cations adsorbed to the negatively charged surface of soil clays, acts as an additional source of soluble salts.

The effects of gypsum dissolution on salinization processes are illustrated through column leaching simulations of gypsiferous and non-gypsiferous loam and clay loam soils using UNSATCHEM software. The results confirm that the presence of gypsum results in an additional salt load produced by the replacement of adsorbed cations by calcium released by gypsum dissolution. While the total amount of additional salt is greater with fine-textured soils due to greater total concentrations of adsorbed cations, the effects are mitigated to a large degree by the lower hydraulic conductivity typical of fine textured soils.

Implications for Modeling and Interpreting Salinization processes Associated with the Alternatives

For the purposes of modeling salinization processes along the Sheyenne River and in Upper Basin wetlands it was assumed that salinity could be modeled using electrical conductivity (EC) or total dissolved solids (TDS) as a single-constituent, non-reactive surrogate for salinity. This assumption was appropriate for illustrative purposes and the resulting models simulate generalized salinization patterns along the Sheyenne River floodplain and in Upper Basin wetlands. However, UNSATCHEM modeling of the effects of gypsum indicated that detailed, predictive modeling of salinization processes must include the effects of gypsum when gypsum is present. The resulting modeling effort necessary to accurately predict salinization processes with time would be complicated by the requirement that all major solute constituents be included in the model. The resulting modeling complexity combined with the heterogeneity inherent in soil chemical and physical features and soil gypsum contents would limit the applicability of large-scale modeling of salinization processes.

Based on our experience with the salinity simulation models, a detailed model could be run that includes laboratory data and actual soil physical and chemical values. However, this effort was beyond the scope of the present study. Such detailed work could be performed at representative sites along the Sheyenne River and the Upper Basin of Devils Lake in the future if such efforts are found to be necessary in order to more accurately assess salinization hazards associated with the alternatives.

TABLE of CONTENTS

LIST OF FIGURES (SEE FIGURES SECTION, ATTACHED)

APPENDICES

Appendix A

Appendix A. UNSATCHEM modeling of the effects of gypsum on soluble salt movement in loam and clay loam soils.

Appendix B. Description of Computer Models Used in the Analysis of Soil Salinization Processes

1. INTRODUCTION

This report supplements two previous reports prepared to assess soil salinization hazards associated with the proposed upper basin storage and constructed outlet alternatives to reduce Devils Lake Flood Damage (Peterson Environmental Consulting, Inc., January 22, 2002; Peterson Environmental Consulting, Inc., February 8, 2002, respectively). The reader is directed to these reports for more detailed background information regarding soil salinization than is provided in the summaries below.

The effects of the alternatives on soil salinity are assessed through computer modeling simulations of salinization processes in specific hydrogeologic settings. While such modeling efforts illustrate the general principles and mechanisms of soil salinization associated with the alternatives, they were not developed for predictive purposes. The principles illustrated in the simulations can be used as a general "guide" in conjunction with the aforementioned reports to evaluate potential salinization risks associated with the alternatives proposed to reduce Devils Lake Flooding.

2. BACKGROUND

2.1. SOIL SALINITY

Soluble salts in general are the products of rock and soil weathering processes (Bresler et al., 1982). In the Northern Plains the interaction of near-surface pore water and constituents in surficial sediments results in unique groundwater chemistries dominated by sulfates of calcium, magnesium and sodium (Groenewald et al., 1983; Hendry et al., 1986). Soil salinity in the Devils Lake area and along the Sheyenne River is associated with sodium and magnesium sulfates released through the weathering of shale and dolomite rock constituents of the local glacial sediments and concentrated by evapotranspiration.

Soluble salts are defined as salts more soluble than gypsum ($CaSO_4 \cdot 2H_2O$), which has a solubility of approximately 2 grams per liter. There are eight ions commonly associated with soluble salts. Cations consist of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+), whereas anions consist of alkalinity (carbonate, CO_3^{2-}; bicarbonate, HCO_3^-, and carbonic acid; H_2CO_3), sulfate (SO_4^{2-}) and chloride (Cl^-). *Soil salinity* is essentially the sum total of soluble salts in the soil, generally limited to the root zone, and is operationally defined by the electrical conductivity of a soil saturation-paste extract (ECspe), expressed in deci-Siemens per meter (dS/m) or micromhos per cm (umho/cm). Total dissolved solids (TDS) expressed as milligrams solute per liter (mg/L) is also used as a salinity surrogate that reflects the sum of individual solutes. Salinity as EC and TDS is related through the relationship:

$$TDS = 0.65*EC \text{ (EC in umho/cm)} \qquad \text{Equation 1}$$

Elevated salt content in the rooting zone of a soil reduces crop yields by competing with plants for water (Bresler et al., 1982). A *salinity hazard* is generally associated with landscape positions characterized by groundwater discharge and shallow water tables (Seelig and Richardson, 1991; Franzen et al., 1994). Soil salinity can be described by the interaction between soil-specific "critical depth" and "critical salinity" parameters. *Critical depth* is defined as the maximum amount that water tables with a given salinity can rise without resulting in salinization of the soil surface. *Critical salinity* is defined as the minimum amount of salt content that near-surface groundwater can have without resulting in salinization of the soil surface, regardless of the water table depth (Maianu, 1981).

A *salinity risk* is the probability that a salinity hazard will become a problem (Bui et al., 1996). Areas at risk of salinization after alteration of water table dynamics are those areas where stored salt is likely to be remobilized and redeposited by rising groundwater tables. Assessing the risk of salinization requires an estimate of preexisting hydrology/salinity and the effects of the altered hydrology induced by elevated water tables.

2.1.1. The Effects of Gypsum on Soil Salinization Processes

Most saline soils in North Dakota contain gypsum to greater or lesser degrees. Gypsum is a sparingly soluble salt whose solubility in pure water is approximately 2 grams per liter. The presence of gypsum can increase the salinization hazard of soils subjected to salt mobilization because calcium ions released as gypsum dissolves are preferentially adsorbed on the cation exchange complex, replacing exchangeable Mg and Na. The Mg and NA so released can then add to the salt load in the groundwater. Thus the exchange complex, consisting of positively charged cations adsorbed to the negatively charged surface of soil clays, acts as an additional source of soluble salts. Because the exchange complex in fine-textured soils especially can represent several grams of potential solute per kilogram of soils, the effects can be significant. The effects of gypsum on soil salinization processes are illustrated in **Appendix A** using the UNSATCHEM computer model for a clay loam soil. A description of the UNSATCHEM model is in **Appendix B**.

2.2. Soil Salinization Hazards associated with the Upper Basin Storage Alternative

The Upper Basin of Devils Lake consists of 2616 square miles in 7 North Dakota counties and encompassing 7 major watersheds. Upper Basin topography is dominated by low, undulating relief with poorly integrated drainage networks. The majority of the acreage in the Upper Basin is agricultural cropland. Conversion of historic wetlands to agricultural use has resulted in the drainage of many prairie wetlands in the upper basin of Devils Lake, North Dakota (Kantrud et al., 1989). Saline soils in the Upper Basin are extensive, and are typically associated with wet areas where the groundwater is at or near the surface.

The Upper Basin Storage (UBS) alternative would reduce flooding in Devils Lake by restoring wetlands that have been partially or effectively drained for agriculture, thus enhancing the storage of water in the upper basin watershed of Devils Lake. Diversions and water-control structures may also be used to provide additional storage. The Upper Basin Storage alternative has the potential to salinize additional lands by raising the water tables in areas adjacent to the storage wetlands.

Salt accumulation in North Dakota is associated with specific hydrogeologic settings generally associated with groundwater discharge, shallow groundwater depths, and infrequent ponding. Salts accumulate in the vadose (i.e. unsaturated) zone when unsaturated flow brings groundwater containing dissolved salts into the rooting zone. The attendant evapotranspirative withdrawal of pure water leaves the salts to accumulate. Although saline soils are the product of long term hydrogeologic conditions, salts are readily mobilized when recharge/discharge/ponding dynamics change. Many discharge-type wetlands with saline soils at the periphery of the historic wetlands have been drained for agriculture in the Upper Basin. Frequently drainage of discharge type wetlands results in a mobilization of salts from the surface to the subsoil at the wetland periphery where water tables are lowered below the critical depth, and from the subsoil to the surface in the pond interior where drainage is often imperfect. The resalinization of the soils at the periphery of the drained historic wetland upon restoration is a possible salinization risk associated with the restoration of discharge type wetlands in the Upper Basin.

Areas at particular risk are existing, imperfectly drained saline or brackish wetlands or areas that are adjacent to wetlands that characteristically have a periphery of saline or saline-sodic soils. Some lateral movement will result in the mobilization of salts from the historic wetland edge to the new edge of the enlarged wetlands. However, it is believed that the majority of the secondary salinization produced by the upper basin storage alternative will result from a mobilization of salts from deep in the profile to the soil surface in areas where the water tables rise above the "critical depth" (defined in section 2.1).

Not all wetlands will be similarly affected. A considerable number of seasonally ponded wetlands have a groundwater recharge function. Soil profiles in these recharge wetlands are typically leached and non-saline. Soils on the periphery of these wetlands are frequently non-saline, somewhat poorly drained Aeric Calciaquolls. A lack of stored salt in these soils combined with the freshness of the runon-component would reduce the salinity risk associated with the restoration of these wetland types.

Two modeling simulations were run to illustrate soil salinization processes associated with the restoration of recharge and discharge wetlands in the upper basin. The recharge wetland simulation consists of an association of Tonka-Hamerly-Svea soils, with Tonka soils occupying the wetland, Hamerly soils occupying the wetland periphery, and Svea soils in the uplands.

The discharge wetland simulation consists of Hegne soils in the wetland, and Hamerly and Hamerly (saline) soils on the wetland periphery and in somewhat poorly drained positions away from the periphery. A sand lens was incorporated into the simulation to illustrate the effects of preferential flow on soil salinization.

2.3. SALINIZATION HAZARDS ASSOCIATED WITH THE OUTLET ALTERNATIVES

The outlet alternatives would alleviate flooding in Devils Lake by releasing under two operating scenarios 300 or 480 cfs of Devils Lake water (extracted from West Bay) through a constructed outlet to the Sheyenne River. Discharge to the Sheyenne River at the highest 480 cfs rate (Unconstrained Scenario) would essentially create high-water conditions that would persist through the fall depending upon natural base-flow and precipitation characteristics. Discharge at the lower 300 cfs rate (Constrained Scenario) would be constrained by sulfate water quality standards and Sheyenne River channel capacity, and would result in limited over-the-bank flooding. The No Action alternative assumes a natural spill from Stump Lake to the Sheyenne River via the Tolna Coulee. Under the No Action alternative, salinity (as TDS) in the Sheyenne River downstream of the spill has been predicted to reach levels as high as 3000 mg/L.

Floodplain soils along the Sheyenne River have developed in response to the natural flooding-drawdown hydrology of the Sheyenne River combined with groundwater discharge/recharge relationships with adjacent aquifers. The quality of Sheyenne River water, while variable depending upon stage, is fresh as compared to Devils Lake water, and has chemistry usually dominated by calcium/magnesium bicarbonate. However, mixed river- and lake-water would be more saline and sodic than it is under existing conditions. Devils Lake water is moderately saline (West Bay salinity is currently ~ 1500 mg/L TDS) with a chemistry dominated by sodium and magnesium sulfate.

2.3.1. Floodplain soils along the Sheyenne River

Soils along the floodplain of the Sheyenne River are characterized by the presence of moderately well drained soils in upland positions and somewhat poorly drained to poorly drained soils associated with abandoned meanders and backswamp positions where the river is shallowly entrenched. Salinity varies, but most of the mapped saline soils are associated with poorly and very poorly drained positions in the shallowly entrenched reach of the Sheyenne River above Lake Ashtabula (PEC Report dated February 8, 2001).

There are two salinization risks associated with the constructed outlet alternatives:

(1) Induced floodplain salinization resulting from the raising of water tables of floodplain and adjacent soils above a critical depth. The resultant increase in evapotranspiration in the surface soil would, in turn, result in an increased concentration of salts that remain after the pure water has been removed.

(2) Additional salt loading to the floodplain could result from both over-bank flooding with mixed Devils Lake/Sheyenne River water and intrusion of this water into adjacent floodplain soils as infiltrated floodwater and groundwater flow. Seepage outflow of mixed Devils Lake/Sheyenne river water could produce additional salt loading to adjacent floodplain soils during periods when the river is contained within the channel.

Under the West Bay outlet alternative with an unconstrained, 480 cfs discharge rate, floodplain soils adjacent to the Sheyenne River could be frequently inundated spring through fall with more saline and more sodic water. The hydrologic conditions associated with this scenario could affect the salt status of the floodplain soils both by mobilizing existing salts stored in the soil and possibly by adding new salt.

Persistent flooding would not likely occur under the Constrained Outlet scenario as proposed. However, the combined Devils Lake/Sheyenne River discharge would likely result in altered influent/effluent relationships between the surface water in the river and adjacent groundwater systems. Under effluent (seepage) conditions associated with the constrained outlet discharge scenarios, seepage outflow from the river and the subsequent movement of this groundwater away from the channel could result in an increased salinization hazard for susceptible soils adjacent to the River.

2.3.1.1. Soil Salinization in the Upper Reach of the Sheyenne River above Lake Ashtabula

The floodplain of the Sheyenne River upstream of Lake Ashtabula is characterized by a shallowly entrenched river channel, a broad active floodplain and extensive areas of relatively fine textured, poorly and very poorly drained soils occupying backswamp and abandoned meander positions. Due to these characteristics, the majority of the existing saline soils along the Sheyenne River lie upstream of Lake Ashtabula. Three modeling simulations were run on two soil associations typical of shallowly entrenched portions of the Sheyenne River upstream of Lake Ashtabula. The soil associations investigated include the Lamoure-LaDelle-LaPrairie-Ryan and the LaDelle-Ludden-Wahpeton associations described in PEC report dated February 8, 2002. Two modeling simulations assume a relatively high water table with moderately saline soils in the low positions. A third simulation included higher river water salinity and a higher river stage.

2.3.1.2. Soil salinization in the lower reach of the Sheyenne River below Baldhill Dam

A more deeply entrenched river and dramatically reduced acreage of poorly and very poorly drained soils characterizes soil associations downstream of Baldhill Dam. Saline soils are much less extensive, being restricted largely to recently abandoned meanders on the active floodplain. One modeling simulation was run on the Fairdale-Laprairie-LaDelle association that is characteristic of the deeply entrenched portion of the Sheyenne River below Baldhill dam (PEC Report dated February 8, 2002). The simulation assumes a relatively deep water table with slightly to moderately saline soils in the low, abandoned meander positions.

3. METHODS

3.1. INTRODUCTION TO THE MODELING PROCESS

The Hydrus 2D and Meshgen 2D programs developed by the staff of the National Soil Salinity Laboratory (Simunek et al., 1999)[1] were used to simulate the effects of hydrologic alteration under the alternatives on water flow and solute transport. A detailed description of the programs is in Appendix B. Simulations were developed for drained and undrained wetlands in both recharge and discharge hydrologic settings in the Upper Basin of Devils Lake, and in riparian floodplain soils along the Sheyenne River.

Interactions between topography, vegetation, climate, surface water, groundwater and soil chemical processes at a given location can not be explicitly modeled due to the complexity inherent in climate and in sediment and solute distributions. However, these processes can be approximated with conceptual simplifications of the inputs to the model based on field evidence, soil survey data, and applicable literature. Much of the applicable literature on soil-water-salinity interactions is summarized in PEC reports dated January 22, 2002 and February 8, 2002 (e.g. Arndt and Richardson, 1988, 1989, 1992, 1993a, 1993b, 1994; Knuteson et al., 1989;

[1] Hydrus 2D/Meshgen 2D is distributed by the International Ground Water Modeling Center located at the Colorado School of Mines in Golden, Colorado.

LaBaugh, 1988; Mills and Zwarich, 1986; Richardson et al., 1991, 1992, Seelig and Richardson, 1994).

Three groups of input variables are required to model soil salinization processes using Hydrus 2D. The first set of variables provide the initial conditions that represent (1) the topography of the landscape in cross-section profile, (2) the hydrologic characteristics of the soil materials, (3) the initial distribution of hydraulic head, and (4) the initial location and concentration of salts. Salts can be provided as individual solutes. However, modeling individual solutes needlessly complicates the model and frequently results in long run times and model convergence failures. Salinity includes the aggregate concentrations of individual cations and anions. If information on an individual solute or solutes is not required, TDS (mg/L) or EC (umho/cm) are frequently used as salinity surrogates under the assumption that the aggregate value is conservative (i.e. non-reactive).

The second set of variables defines the boundary conditions necessary to run the finite element model. Boundary conditions describe the rules that govern the movement of water into and out of the model cross-section. Boundary conditions must be defined for the entire perimeter of the modeled area and are discussed in detail in section 3.1.2 below.

The last set of variables includes time dependent conditions that represent changing rainfall and vegetation water-use rates over the duration of the model run time. Also included under time dependent conditions are model characteristics that influence the time-step selection and the iterative process used to evaluate groundwater and solute movement. Time-step and iteration criteria frequently need to be changed incrementally during model runs in order to get the model to converge on an answer without failing (crashing).

The modeling process takes initial conditions and then applies a stressor such as increasing the magnitude of groundwater additions or deletions. The effects of the stressors are calculated for each timestep until a convergence is reached and successive iterations result in insignificant changes in the parameters of interest determined by comparison to set tolerance levels. For more information see the Hydrus 2D manual (Simunek et al., 1999).

3.1.1. Development of the Finite Element Model

Meshgen 2D discritizes a two-dimensional closed polygon representing a landscape cross-section into discrete elements forming a distribution of nodes that can be attributed with parameters representing initial conditions (discussed below). The effects of the stressors on the parameters of interest are then calculated at each node.

The periphery of the landscape cross-section provides the boundary that must be attributed with appropriate boundary conditions. Landscape cross-sections representing both recharge and discharge wetlands were developed from an idealized landscape setting representing a relatively gentle slope from the upland to the wetland. The cross-sections represent a 350-by-12 meter “slice” perpendicular to the wetland boundary and extending to the center of the wetland. Examples of the idealized cross-sections are provided for both the recharge simulation and the discharge simulation in figures cited in section 3.1.5 below.

Landscape cross-sections applicable to the Sheyenne River were developed from the detailed Lidar DEM data provided by the St. Paul District of the USACE. Elevations along a transect developed from the river centerline to the edge of the floodplain were determined in Arcview using *Spatial Analyst* and *Profile Extractor* extensions. Transect elevations form the top undulating surface of the cross-section. Orthogonal bounding lines were then drawn to form the closed polygon necessary for discritization. Examples of the idealized cross-sections for both the recharge and the discharge simulations are provided in figures cited below in section 3.1.5.

3.1.2. Boundary Conditions

Simulations developed to model soil salinization processes include the following boundary conditions. A detailed discussion of boundary conditions is in Franke et al. (1987) and is available on the World Wide Web (WWW) at url:

http://www.mines.edu/research/igwmc/thought/boundary/

A representative cross-section with appropriate boundary conditions is provided in **Figure 1** for reference. Boundary conditions associated with each simulation are provided in the figures cited in section 3.1.5 below.

- **No Flow Boundary**: A no flow boundary condition represents either an impermeable layer or a streamline or stream-surface boundary across which no water will flow. Many groundwater models involving lakes, ponds, and streams are set up so that the center of the lake, pond, or stream represents an axis of symmetry across which no water will flow. Recharge and discharge Upper Basin wetlands simulated in this study use the center of the pond and the bottom of the section as no flow boundaries. Similarly, soil salinization simulations developed for floodplain settings along the Sheyenne River use the centerline of the river and the bottom of the section as no-flow boundaries.

- **Variable Head Boundary**: A variable head boundary represents a surface where water movement across the surface changes in response to changes in head in the material adjacent to the boundary. The hydraulic head across a variable head boundary can then change dependent upon time-variable fluxes in water content within the model.

- **Atmospheric Boundary**: the Atmospheric boundary is also known as a “free surface” boundary. The most common atmospheric boundary is the water table surface at some point in time. The hydraulic head at the atmospheric boundary is always at atmospheric pressure. However, the position of an atmospheric boundary is not fixed, but is free to vary dependent upon water fluxes into or out of the section being modeled.

- **Constant Head Boundary**: A constant head boundary is a boundary where the hydraulic head remains constant throughout the simulation. Water sources at constant head boundaries are assumed to be capable of supplying an infinite amount of water to the system such that the water levels do not drop under the simulation. The hydraulic heads associated with rivers, lakes, and ponds are frequently assumed to be constant head boundaries.

- **Seepage Face Boundary**: A seepage face boundary is a boundary between the saturated flow field and the atmosphere along which groundwater discharges. The pressure is assumed to be atmospheric along a seepage face boundary. Any groundwater discharge is assumed to be removed by flow or evaporation. Seepage-face boundaries become atmospheric boundaries if and when the head becomes negative along part or all of the seepage face due to a lowering of the water table.

3.1.3. Selection of Initial Conditions

Modeling dictates that appropriate initial conditions be selected to represent as accurately as possible the situation associated with the landforms and substrate being modeled. Initial textural characteristics provided for soils remain constant. However, the initial conditions provided for hydraulic head, solute concentration, and unsaturated flow parameters in the soils vary with time during the modeling runs, and indeed are the focus of the simulation. Some initial conditions can be constant or can vary with time. For example, while root distribution remains constant, transpiration can and does vary with moisture content and solute stress. The Hydrus 2D model frequently permits the selection of whether or not such parameters are held constant or are allowed to vary. However, the inclusion of progressively more time-dependent information results in longer run times and model destabilization that can, in turn, result in frequent convergence failures. Because this discussion emphasizes the overall processes, simplifications and constant conditions were used to the extent possible (discussed in section 3.1.4 below).

3.1.3.1. Soils and substrates

Soil material distribution was based on Natural Resources Conservation Service (NRCS) official soil series descriptions (OSDs) for the appropriate area, and knowledge of soil characteristics obtained from field work, county soil surveys, and applicable literature described in detail in PEC reports dated January 22, 2002 and February 8, 2002. Hydrus 2D includes the Rosetta program (see Appendix B) that provides estimates of saturated and unsaturated hydraulic properties depending upon increasing levels of detail in hydraulic information regarding the soil. For the purposes of the present simulations, all necessary saturated and unsaturated soil hydraulic properties were based on the soil texture applicable to the soils used in the simulation. Examples of soils and substrates used for all simulations are provided in figures cited below in section 3.1.5.

3.1.3.2. Plant Root Effects

Transpiration by plant roots represents a water loss that occurs within the soil profile that can result in the concentration of salts to high values within the rooting zone. Hydrus 2D provides a module to identify the distribution of roots with depth and estimate the amount of water transpired based on tabulated values for individual crops at varying soil moisture contents. The module also permits the entry of individual values relating to crop water use if they are known or are obtained experimentally. Because this report focuses on a comparison of general salinization processes, all simulations used default alfalfa crop water loss values as tabulated in Hydrus 2D. Alfalfa is a common, relatively deep-rooted crop in the Northern Plains that should reflect realistic plant water-use values.

Crop water-use can be adversely affected by the amount of solute present in the soil (solute stress). Solute stress was not included as a component of the simulations used in the present study as its inclusion resulted in longer run times and frequent model failures. Examples of the initial plant root distribution used for all simulations are provided in figures cited below in section 3.1.5.

3.1.3.3. Hydraulic Head

Initial hydraulic head values appropriate to the landscape settings of the simulation were used. A pair of model runs for the Sheyenne River simulations used two different initial hydraulic head and river-water salinity values to simulate the effects of the Sheyenne River stage on soil salinization processes. Initial head values used in the Upper Basin recharge and discharge wetland simulations reflected the restoration of the pond to the natural conditions. However, the pond stage was set as a constant head boundary in order to facilitate model run time and prevent model failures. Examples of initial hydraulic heads used for all simulations are provided in figures cited below in section 3.1.5.

3.1.3.4. Solute Concentration

Solute concentrations in soils and surface water were similarly set at realistic values based on the landscape setting, applicable literature, soil survey data, and field determinations using an EM-38 above-ground soil conductivity meter (Arndt et al., 1987). Solutes were modeled as a single conservative tracer as a surrogate representing TDS (as ppm) or EC (as mmhos/cm). A pair of model runs used varying concentrations of Sheyenne River water to assess the effects of varying salinity under the alternatives. Examples of initial solute concentrations used for all simulations are provided in figures cited below in section 3.1.5.

3.1.3.5. Precipitation and Evapotranspiration

Time variable conditions in the simulations represent rainfall and crop water-loss data distributed over a 180-day period beginning April 1. This time period was used because it essentially represents the growing season. Precipitation data represent actual weather data collected from April 1, 2001, through September 30, 2001. The data was collected from the Carrington, North Dakota, weather station obtained from the North Dakota Agricultural Weather Network (NDAWN) Web Site.

<http://www.ext.nodak.edu/weather/ndawn/carrington/>

Because this report focuses on a comparison of general salinization processes, all simulations used alfalfa crop water-loss values. To simplify the modeling process the rainfall and crop water loss (CWL) data daily values were summarized and averaged for each month equaling 30 days. Monthly rainfall values were subtracted from the crop water loss values. This value was then divided by the days in each representative month. The resulting values represent the net crop water loss per day over the 180-day run time of the model, and furthermore represent a net precipitation/evapotranspiration ratio less than one that is characteristic of sub-humid climates where evapotranspiration is in excess of precipitation.

Table 1. Precipitation data used in the simulations

	Inches /month	Inches per day	Meter per day
April	0.57	0.019	0.000475
May	2.11	0.068	0.0017
June	4.80	0.16	0.004
July	5.61	0.18	0.0045
August	1.16	0.037	0.00925
September	0.77	0.025	0.000625

Table 2. Crop water use data and net crop water loss

	Inches /month	Inches per day	Meter per day	Net CWL[1]
April	2.09	0.069	0.001725	0.00125
May	5.00	0.166	0.00415	0.00245
June	5.34	0.178	0.00445	0.00045
July	7.18	0.2316	0.00579	0.00129
August	7.03	0.235	0.005875	0.0049
September	2.07	0.069	0.001725	0.0011

[1]Net Crop water-loss (CWL) was calculated as precipitation (as meters per day, Table 1) subtracted from crop water use (in meters per day, Table 2).

3.1.4. Assumptions and Simplifications

The following assumptions and simplifications used in the salinity modeling simulations affect the interpretation of the results to greater or lesser degrees. However, while the effects may change salinity values, the overall patterns of salinization and the interpretations based on them would not change.

3.1.4.1. Initial Hydraulic Head Values and Boundary Conditions

Constant head values were used to represent wetlands and river stages where in actuality water levels in wetlands and rivers naturally vary. Water levels in recharge wetlands in particular would normally drop to below the ground surface over the growing season. The assumption of a relatively constant head in discharge wetlands and in the Sheyenne River is a realistic assumption that should average out transient variations that could mask overall trends. The varying stages in wetlands and the river would result in changes in the direction of water flow that, when averaged over time, would result in a net movement in a specific direction. This "averaged" value would better reflect the overall processes of soil salinization and reduce the "noise" provided by transient conditions. With respect to the recharge wetland modeled for the upper basin, reintroducing the initial head conditions that reflect an unsaturated zone sandwiched between the pond and the groundwater mound simulates the natural yearly fall-drawdown and spring-recharge condition.

Constant head boundaries were also used to represent a constant level of groundwater discharge from the uplands adjacent to the Sheyenne River. In lieu of actual data indicating otherwise, the assumption of a small amount of discharge from upland positions is realistic given the hydrogeological setting of the Sheyenne River as an underfit stream meandering through a large glacial valley.

The use of a no flow boundary to represent the center of the wetland and the centerline of the Sheyenne River is justified by model symmetry. A no-flow boundary condition was chosen to represent the bottom of the section which varied in thickness from 12 to 16 meters (40-50 feet) This assumption is realistic given the hydrogeological setting of the river where the majority of the groundwater flow would be near the surface.

3.1.4.2. Precipitation and Evapotranspiration

Initial attempts to incorporate daily precipitation, evaporation, and transpiration values resulted in extremely long model run-times and numerous convergence failures. Because the simulations were designed to illustrate salinization processes in a general and comparative way, the choice of incorporating precipitation, transpiration, and evaporation into a single number reflective of a net loss of water over the growing season was chosen to more efficiently model salinization processes. The results effectively represent long-term natural conditions where precipitation/evapotranspiration ratios are less than one, indicating a net precipitation deficit during the growing season with recharge occurring during spring. The effects of transient pluvial (wet) conditions on leaching salts downward into the profile is only represented during spring conditions when high water tables are assumed as an initial condition.

3.1.4.3. Roots

For comparative purposes, the effects of transpiration on solute concentration within the root zone were modeled using alfalfa, with root densities decreasing from the surface to about 1 meter in depth. In order to simplify model conditions, the effects of solute concentration on crop water-use were not modeled. In actuality, where the simulations predict that concentration values will rise above approximately 4000 units, crop water use will decline due to solute stress. Reduced transporation would result in lower concentration within the rooting zone and higher concentrations near the soil surface. However, interpretations of landscape salinization processes would not be affected to a substantive degree by the lack of a solute stress component in model simulations.

3.1.5. Initial and Boundary Conditions

Initial and boundary conditions for all simulations are provided and discussed in **Figures 2 through 7**. Specific details regarding the initial and boundary conditions are provided as text associated with each figure. Each figure follows the same pattern. The following list explains the conditions and parameters provided in the figure text.

Part A. Presents the finite element mesh used to discritize initial conditions and run the model.

Part B. Presents the boundary conditions associated with the perimeter of the section.

Part C. Presents the soils and material distribution attributed for each node in the mesh.

Part D. Presents the distribution of roots in the surface.

Part E. Presents the initial head distribution.

Part F. Presents the initial solute concentration in arbitrary units representative of EC or TDS.

Figure 2. Upper Basin Alternative, Recharge Wetland. Initial and boundary conditions for the recharge wetland simulation represent the restoration of a recharge type wetland with Tonka soils drained by ditching the center of the wetland. Hamerly soils occupy the wetland periphery, and Svea soils are dominant in the uplands. For greater detail on the salinity and spatial distribution of these soils, see PEC report dated January 22, 2002.

Figure 3. Upper Basin Alternative, Discharge Wetland. Initial and boundary conditions for the discharge wetland simulation represent the restoration of a moderately saline discharge wetland drained by ditching the center of the wetland. Hegne soils occupy the historic wetland, with Hammerly and Hamerly (saline) soils on the wetland periphery and in somewhat poorly drained positions away from the wetland periphery. A sand lens has been introduced to evaluate the effects of preferential flow. For greater detail on the salinity and spatial distribution of these soils, see PEC report dated January 22, 2002.

Figure 4. Outlet Alternative, Sheyenne River Upper Reach 1. The initial and boundary conditions for the simulation represent salinization processes associated with upstream reaches of the Sheyenne River characterized by shallow entrenchment and an association of Lamoure, LaDelle, Laprairie and Ryan soils. Saline soils are common in poorly drained landscape positions. For greater detail on the salinity and spatial distribution of these soils, see PEC Report dated February 8, 2002.

Figure 5. Outlet Alternative, Sheyenne River Upper Reach 2. The initial and boundary conditions for the simulation represent salinization processes associated with upstream reaches of the Sheyenne River that are characterized by shallow entrenchment and an association of LaDelle, Ludden, and Wahpeton soils. Saline soils are common in poorly drained landscape positions. For greater detail on the salinity and spatial distribution of these soils, see PEC Report dated February 8, 2002.

Figure 6. Outlet Alternative, Sheyenne River Upper Reach 3. The initial and boundary conditions for the simulation use the same initial conditions as those in Figure 5 with the exception that the stage and salinity of the river has been increased (compare Figure 5F with Figure 6F).

Figure 7. Outlet Alternative, Sheyenne River Lower Reach 1. The initial and boundary conditions for the simulation represent salinization processes associated with downstream reaches of the Sheyenne River below Baldhill Dam that are characterized by a deep entrenchment and an association of Fairdale, LaPrairie, and LaDelle soils.

3.1.6. Model runs

Simulations consisted of up to 10 separate runs, one for each of up to 10 successive years; however, salinization patterns are usually evident within 5 years. Each model has a run time of 180 days using the initial and boundary conditions and the time variable conditions described above and provided in the appropriate figures cited below. The first year simulates the restoration of hydrological processes representative of late spring conditions. For the recharge and discharge wetland the initial conditions assumed that the wetland was restored to the natural condition. Successive years were modeled by importing the year-end (180-day) salinity distribution from the previous year to be used as the next year's initial salinity condition. All successive models used the initial ground water conditions established for the beginning of the first year.

4. RESULTS AND DISCUSSION

Results of model runs are presented along with a discussion in **Figures 8 through 13**. Specific details regarding the hydrogeological setting and the specifics of the salinization simulation are provided as text associated with each figure. Each figure follows the same pattern and is designed to act as a stand-alone discussion of the dominant soil salinization characteristics of the simulation. The following list explains the conditions and parameters provided in the figure text.

Part A. Provides the physical setting and water table configuration of the cross section for days 1, 90, and 180 of the simulation. Water table configurations for each subsequent simulation will be the same because year-1 initial hydrologic head conditions are imposed at the beginning of each successive modeling year. Also included are idealized saturated and unsaturated flow direction, and miscellaneous notes and discussion applicable to the individual simulation.

Part B. Provides the modeled salinity distribution for a representative series of simulation years, usually illustrating salinity distribution at Day 1, Year1, day 180 year 1, Day 180 year 3, and Day 180, Year 5. Pertinent parameters applicable to the individual simulation are provided as callouts on the figures and as figure text.

Figure 8. Examines simulated water table configuration, saturation dynamics, and salinity distribution associated with the modeling of an idealized, restored Upper Basin recharge wetland dominated by Tonka and Hamerly soils, with Svea soils in the upland.

Figure 9. Examines water table configuration, saturation dynamics, and salinity distribution associated with the modeling of an idealized, restored Upper Basin discharge wetland dominated by Hegne and Hamerly soils, with Hamerly (saline) soil variants in the upland position.

Figure 10. Examines water table configuration, saturation dynamics, and salinity distribution associated with the modeling of an idealized Lamoure-Ladelle-LaPrairie-Ryan soil association typical of fine-textured alluvial soils on low floodplains of the upper reaches of the Sheyenne River above Lake Ashtabula.

Figure 11. Examines water table configuration, saturation dynamics, and salinity distribution associated with the modeling of an idealized Ladelle-Ludden-Wahpeton soil association typical of fine and medium textured alluvial soils on low floodplains of the upper reaches of the Sheyenne River above Lake Ashtabula.

Figure 12. Examines water table configuration, saturation dynamics, and salinity distribution associated with the modeling of an idealized Ladelle-Ludden-Wahpeton soil association typical of fine and medium textured alluvial soils on low floodplains of the upper reaches of the Sheyenne River above Lake Ashtabula. The simulation is similar to that in Figure 11, but includes high river-water salinity and a higher river stage.

Figure 13. Examines water table configuration, saturation dynamics, and salinity distribution associated with the modeling of an idealized Fairdale-LaPrairie-LaDelle soil association typical of alluvial soils on floodplains of the entrenched Sheyenne River below Baldhill Dam.

5. CONCLUSIONS

Hydrus 2D simulations illustrate the processes involved in the movement and accumulation of soluble salts in Upper Basin wetlands and in floodplain soils along the Sheyenne River. The following conclusions are drawn regarding the simulations illustrated in Figures 2-7 and 8-13.

5.1. UPPER BASIN SOIL SALINIZATION SIMULATIONS

1. A soil salinity hazard requires the presence of high levels of salts near the soil surface. In the absence of such accumulations, the restoration of recharge wetlands has a little risk of soil salinization. Minor edge-focused salinization typical of that found under natural conditions was observed in simulation, but not to levels that would result in substantive crop yield reductions.

2. Drained discharge wetlands typically have substantial amounts of subsoil salts that constitute a salinization hazard upon restoration. Salts can be mobilized to the surface by increasing the elevation of water tables adjacent to the restored wetland. Salts can also preferentially be transported along sand lenses that can act as a conduit for water flow from the restored wetland. Relatively rapid salinization to levels that could reduce crop yields can occur under these circumstances.

5.2. SHEYENNE RIVER SOIL SALINIZATION SIMULATIONS

1. Poorly and very poorly drained soils on the floodplain of the Sheyenne River accumulate salts because upward unsaturated groundwater-flow accumulates salts at the surface as evapotranspiration removes pure water. Salinization is greatest in low positions where the water table is above a “critical depth.” Salinization becomes progressively less as the depth to the water table increases.

2. In soils with low hydraulic conductivity (e.g. clay loam) the removal of water by evapotranspiration can exceed replacement by groundwater flow from the river, resulting in a groundwater depression during summer where the water levels in floodplain soils distant from the river are lower than the river stage.

3. Increasing the stage and salinity of the Sheyenne River can result in additional salinization of soils adjacent to the river. However, the data indicate that the increased salinization will be primarily confined to soils immediately adjacent to the river when those soils have characteristic, low hydraulic conductivity. Data from county soil surveys suggests that coarse textured soils are relatively rare on the floodplain of the Sheyenne River.

4. While groundwater intrusion is limited to areas immediately adjacent to the river, increased flooding under the outlet alternatives could result in a salinization hazard induced by regular flooding persistently raising water tables

5. Increased salinization of moderately well drained floodplain soils on the elevated floodplains above the entrenched Sheyenne River downstream of Baldhill Dam is unlikely because the water tables would be well below the critical depth required for soil salinization.

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Figures

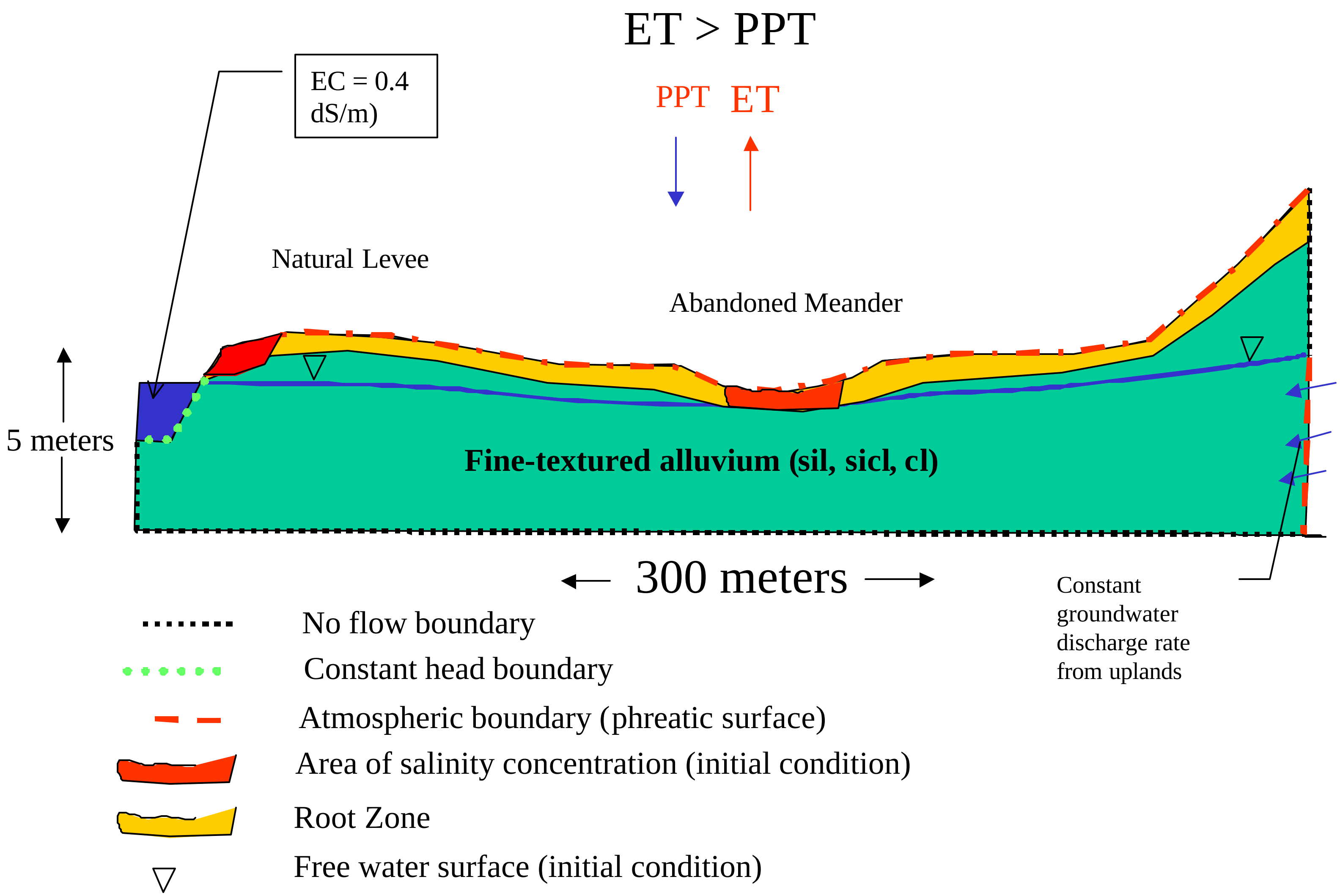
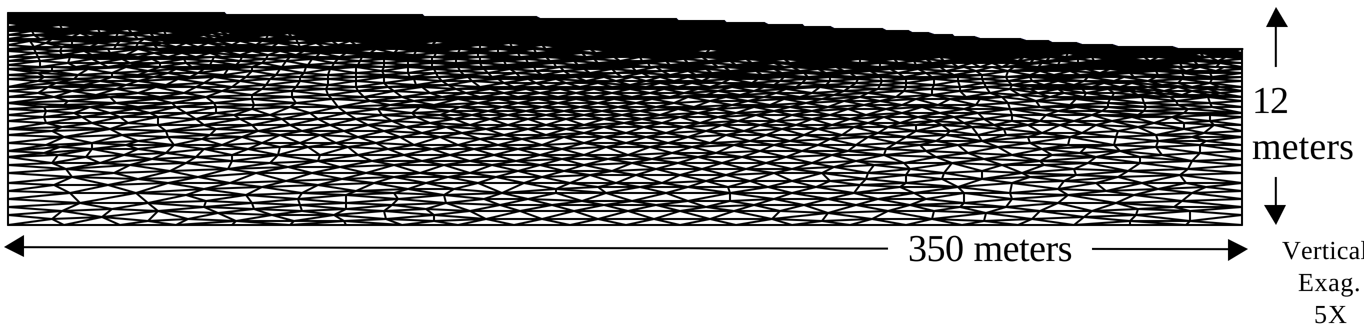


Figure 1. Conceptual setting for salinity modeling along an idealized cross-section of the Sheyenne River Valley floodplain. This figure was discussed with the staff of the NSSL, Riverside California to ensure appropriate concepts, boundary conditions, and initial conditions were used for the Hydrus 2D modeling. Note that boundary conditions have been set for the entire perimeter of the section. Note floodplain geomorphology and placement of the natural levee and the abandoned meander. The cross section would be representative of the shallowly entrenched reach of the Sheyenne River above Lake Ashtabula.

Figure 2. Modeling parameters and initial and boundary conditions for an idealized Upper Basin recharge wetland dominated by Tonka and Hamerly soils, with Svea soils in the upland.

Mesh

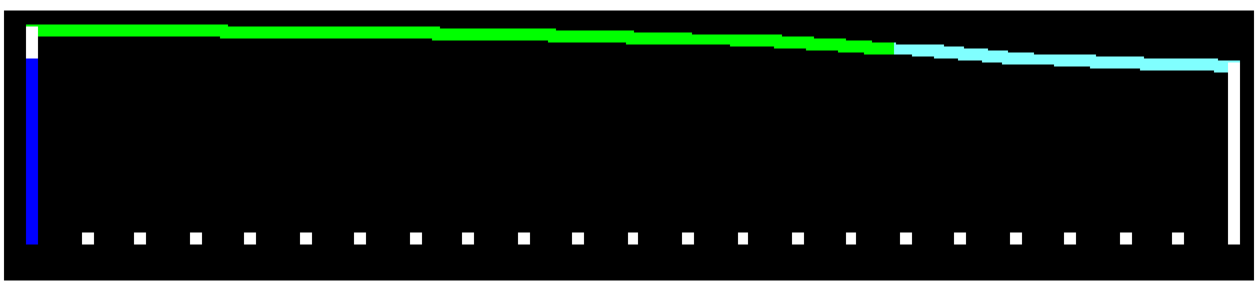
A



Mesh generated in Meshgen for the discritization of initial conditions and running the finite element model. A denser mesh is required near the soil surface where head and concentration gradients are greatest.

Boundary Conditions

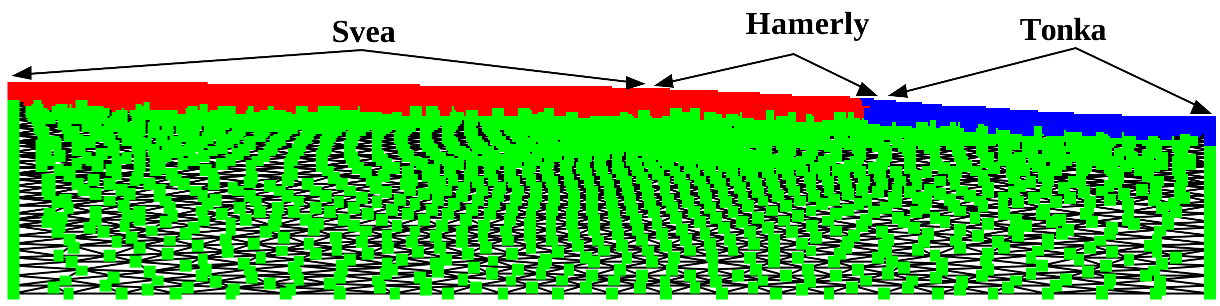
B



Boundary Conditions:
Dark Blue: Variable head
White: No Flow
Green: Atmospheric
Sky Blue: Constant head (represents pond after restoration)

Soils Distribution

C



Material Distribution:
Red: Loam
Blue: Silty clay loam
Green: Clay loam

Tonka, Hamerly, and Svea soils are discussed in section 3.1.1 of PEC Report dated February 8, 2002.

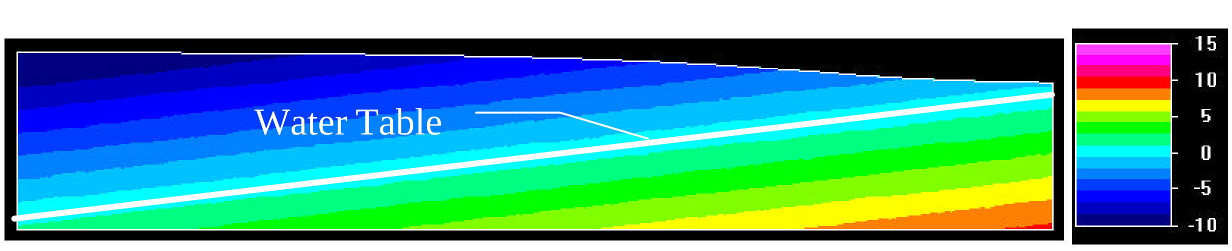
Roots

D

Root distribution (yellow) was chosen to be evenly distributed with depth.

Initial Head Distribution

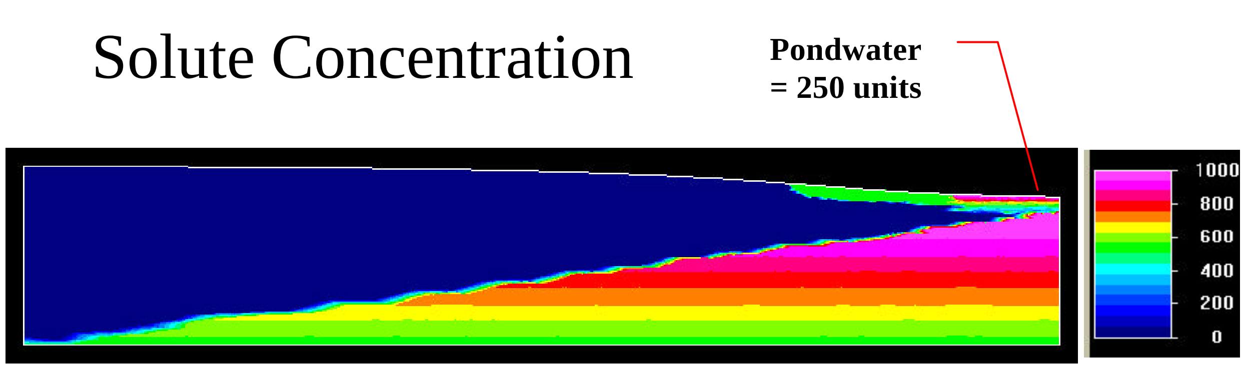
E



Initial head distribution is representative of a groundwater mound under the recharge wetland. Restoration will cause the growth of the groundwater mound to include the restored wetland.

Solute Concentration

F

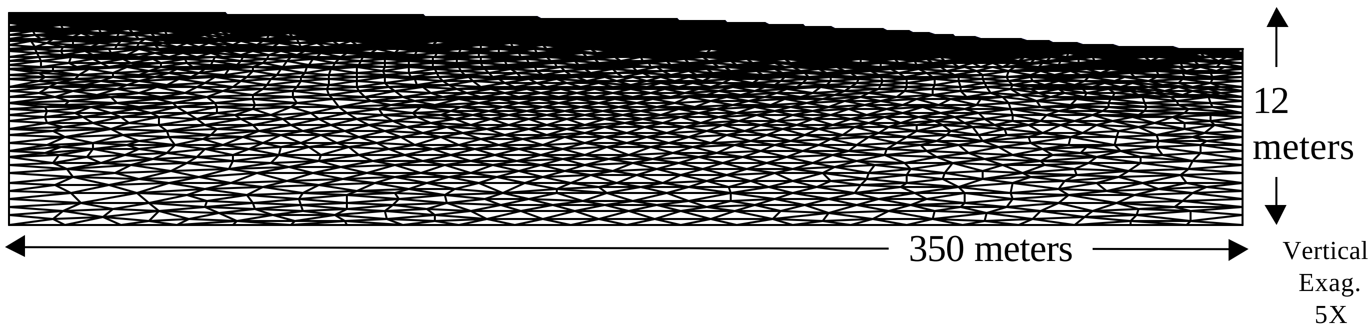


Overall concentration of salts are low in areas associated with recharge wetlands. Initial solute concentrations were chosen to be greatest adjacent to the drain, with moderate concentrations associated with the soil surface at the edge of the drained wetland. Solute concentrations in upland areas were set at 100 units. The concentration of recharging pond-water was set at 250 units.

Figure 3. Modeling parameters and initial and boundary conditions for an idealized Upper Basin discharge-wetland dominated by Hegne and Hamerly soils.

Mesh

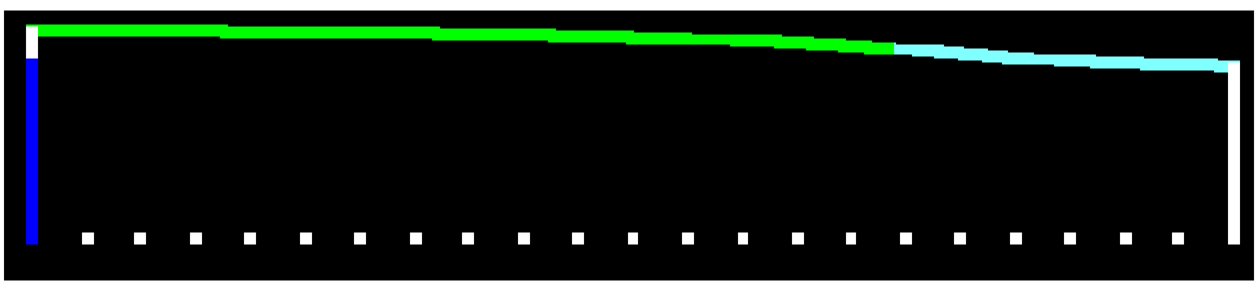
A



Mesh generated in Meshgen for the discritization of initial conditions and running the finite element model. A denser mesh is required near the soil surface where head and concentration gradients are greatest.

Boundary Conditions

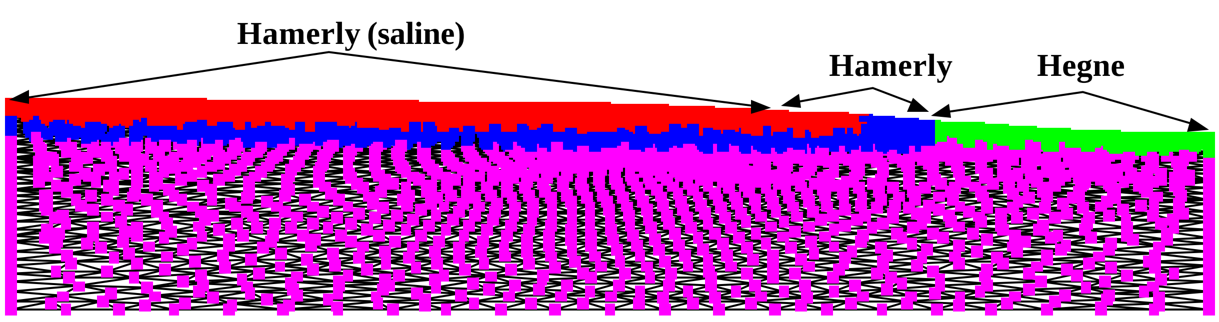
B



Boundary Conditions:
Dark Blue: Variable head
White: No Flow
Green: Atmospheric
Sky Blue: Constant head (represents pond after restoration

Soils Distribution

C



Material Distribution:
Red: Loam
Blue: Sandy loam
Magenta: Clay loam
Green: Silty clay loam

Note that the Hamerly soil includes a sand lens. Such lenses are common in soils around semipermanent wetlands in North Dakota. Typical soils are discussed in section 3.1.3 of PEC Report dated February 8, 2002.

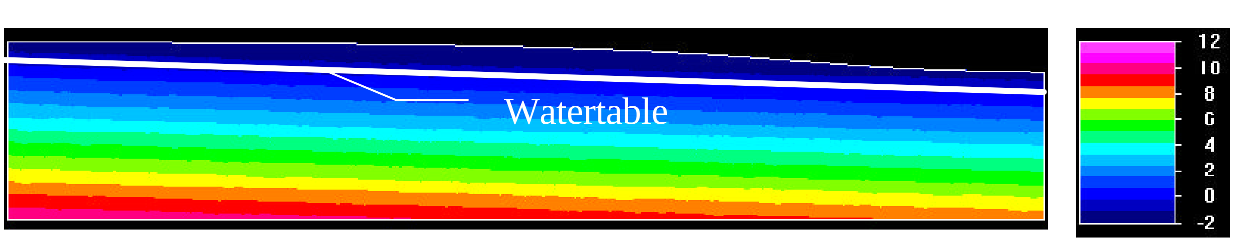
Roots

D

Root distribution (yellow) was chosen to be evenly distributed with depth in the loamy material over the loamy sand.

Initial Head Distribution

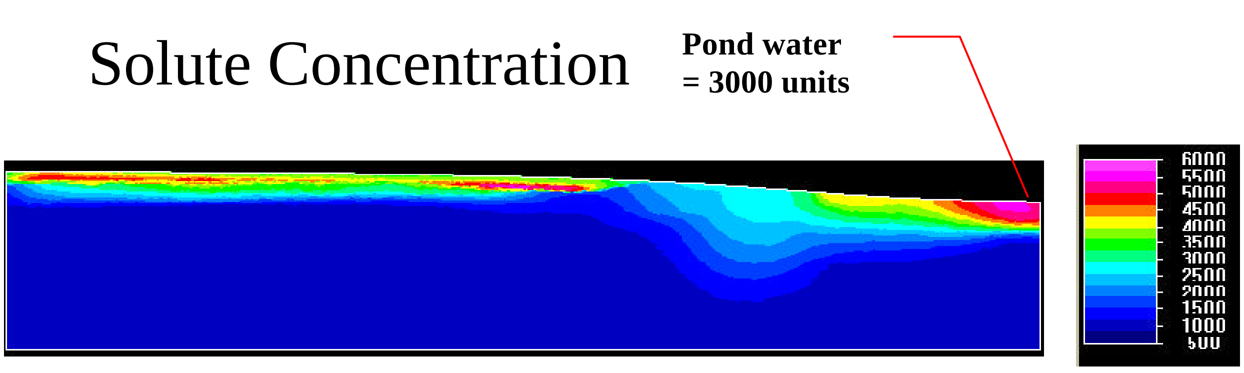
E



Initial head distribution shows a low gradient directed to the discharge wetland. Water tables are high throughout the area. Wetland restoration will cause a groundwater mound to develop that would saturate the sand lens (see C above). The sand lens could then act as a conduit for brackish water from the wetland and from the subsurface.

Solute Concentration

F



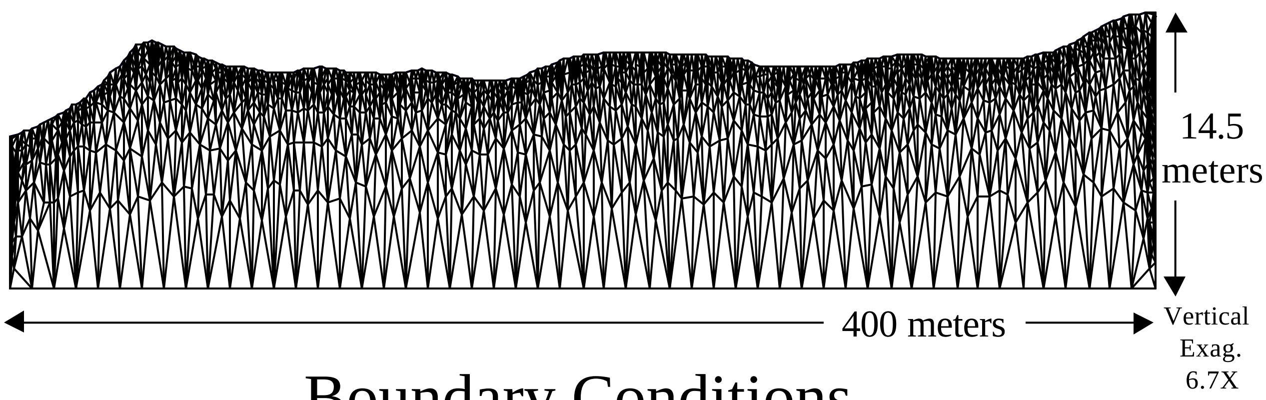
Initial solute concentrations chosen to be greatest adjacent to the drain, with moderate concentrations associated with the bed and edge of the drained wetland and the loamy material over the sand lens. Subsurface material was given an initial concentration of 1000 units. Pondwater was given a concentration of 3000 units.

The restoration should result in rapid salinization of the soil above the sand lens, and a slow movement of salts from the pond to the pond edge.

Figure 4. Modeling parameters and initial and boundary conditions for an idealized Lamoure-LaDelle-LaPrairie-Ryan soil association typical of fine-textured alluvial soils on low floodplains of the upper reaches of the Sheyenne River above Lake Ashtabula.

Mesh

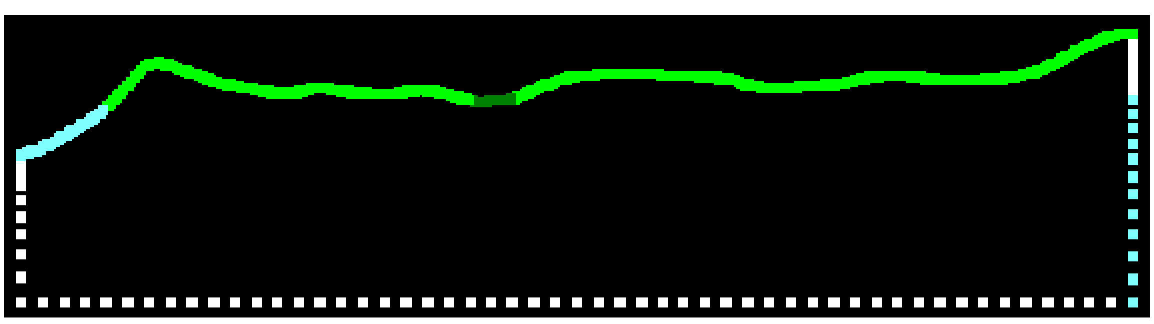
A



Mesh generated in Meshgen for the discritization of initial conditions and running the finite element model. A denser mesh is required near the soil surface where head and concentration gradients are greatest. Cross-section elevations were taken from a representative section along the Sheyenne River below Peterson Coulee.

Boundary Conditions

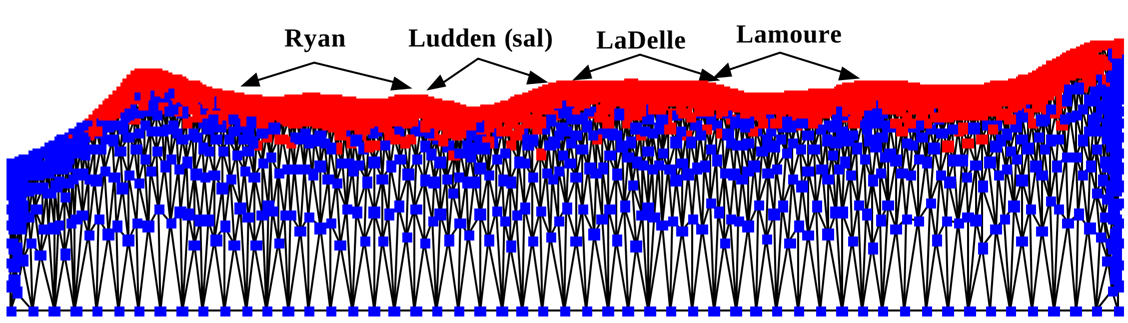
B



Boundary Conditions:
White: No Flow
Green: Atmospheric
Sky Blue: Constant head
Dark Green: Seepage face

Soils Distribution

C

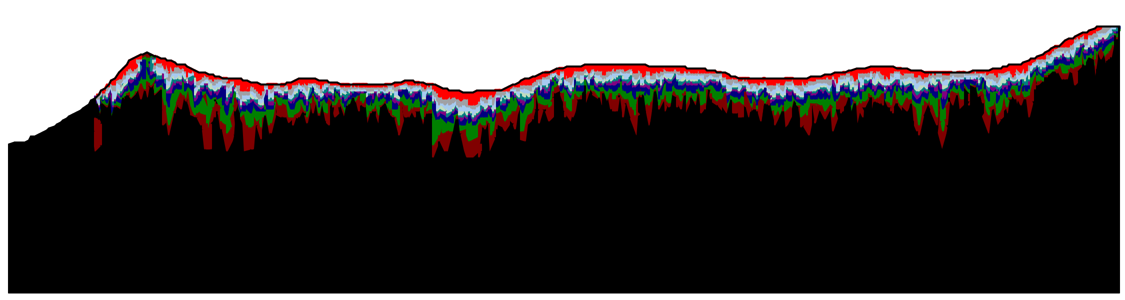


Material Distribution:
Red: Silty clay loam
Blue: Clay Loam

Note that these alluvial soils consist of Moderately well drained to poorly drained, fine textured sediments with high water holding capacities and thick capillary fringes. Soils are discussed in section 4.2.2.1 of PEC Report dated January 22, 2002.

Roots

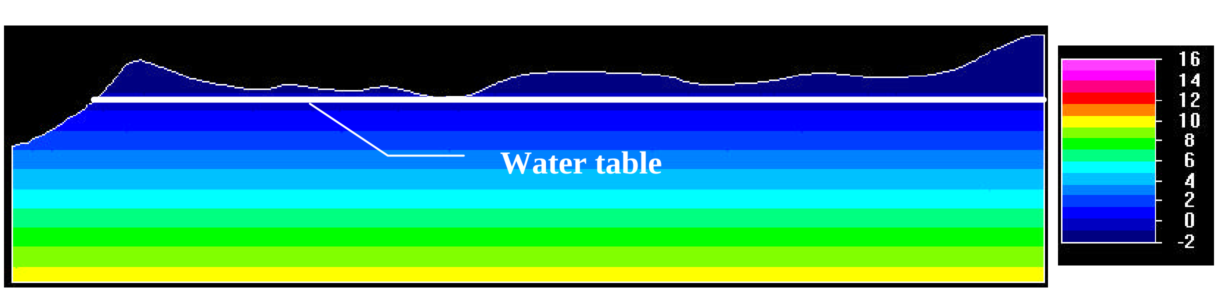
D



Root density (non-black colors) was chosen to be greatest at the surface (red), and declining with depth.

Initial Head Distribution

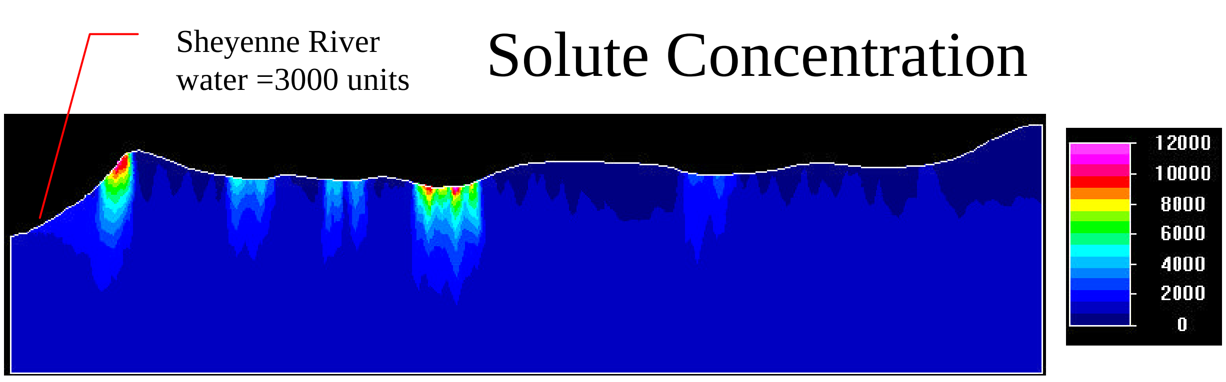
E



Initial head distribution assumes a flat, elevated watertable near the soil surface that would be typical of spring runoff and flooding conditions. Water is very near or at the surface in the low areas dominated by Ludden (saline), Lamoure, and Ryan soils.

Solute Concentration

F



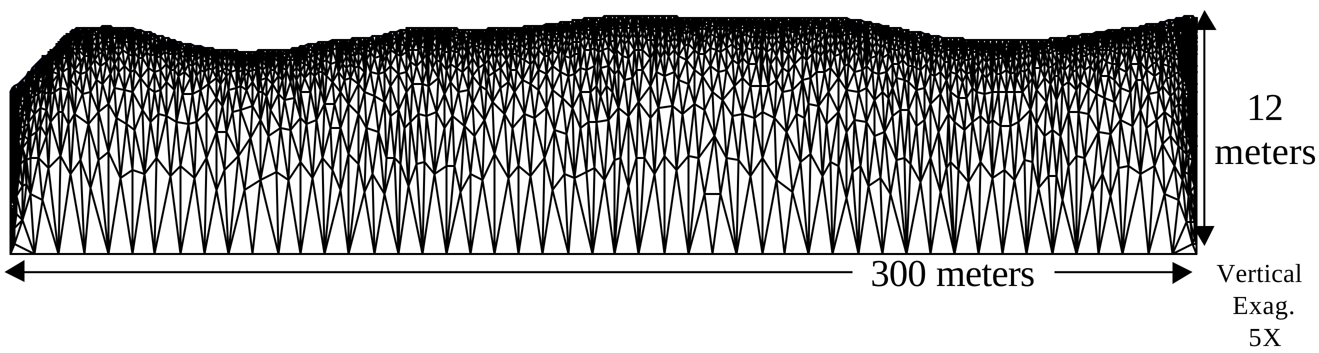
Solute concentrations associated with low abandoned meanders was based on EM-38 and soil survey data and are typical of soils in these positions. The highest salinity is associated with the poorly drained Ludden (saline) soil. Lowest salinity is associated with the moderately well drained LaDelle soil. Underlying substrate alluvium was given an initial concentration of 1000 units.

In order to investigate intrusion of Sheyenne River water into the adjacent soils, the solute concentration of the Sheyenne River water was fixed at 3000 units.

Figure 5. Modeling parameters and initial and boundary conditions for an idealized LaDelle-Ludden-Wahpeton soil association typical of alluvial soils on low floodplains of the Sheyenne river above Lake Ashtabula.

Mesh

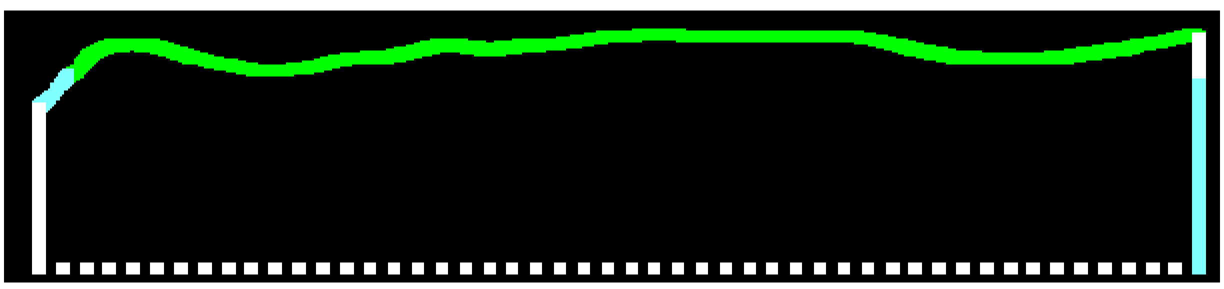
A



Mesh generated in Meshgen for the discritization of initial conditions and running the finite element model. A denser mesh is required near the soil surface where head and concentration gradients are greatest. Cross-section elevations taken from a representative section along the Sheyenne River near the Cooperstown control point.

Boundary Conditions

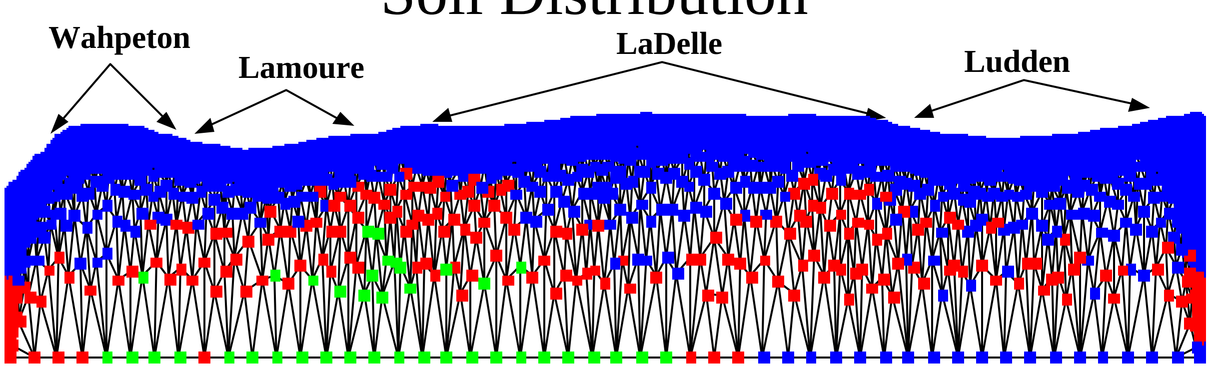
B



Boundary Conditions:
White: No Flow
Green: Atmospheric
Sky Blue: Constant head

Soil Distribution

C

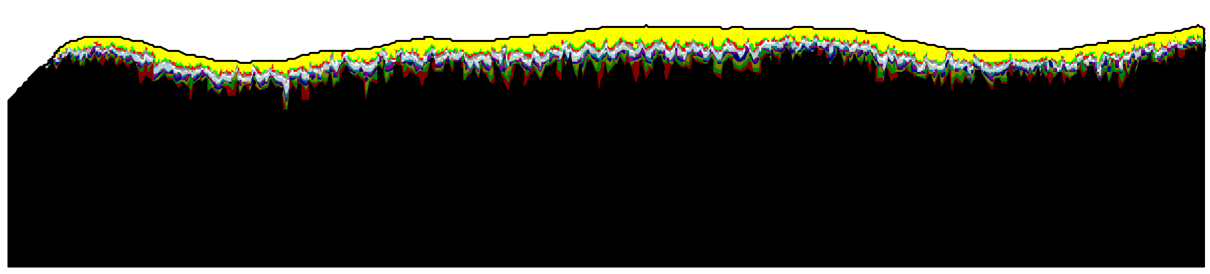


Material Distribution:
Red: Loam
Blue: Silty clay Loam
Green: Clay loam

Note that these alluvial soils consist of moderately well drained to poorly drained fine and medium textured sediments. Soils in the LaDelle-Ludden-Wahpeton association are discussed in section 4.2.2.2 of PEC Report dated January 22, 2002

Roots

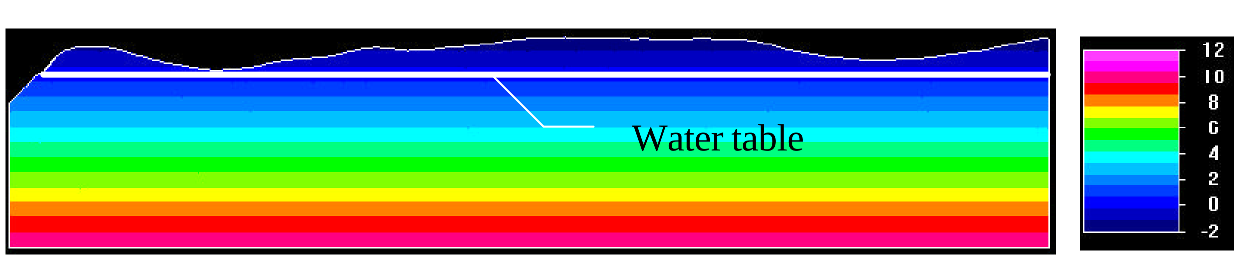
D



Root density (non-black colors) was chosen to be greatest at the surface (yellow), and declining with depth.

Initial Head Distribution

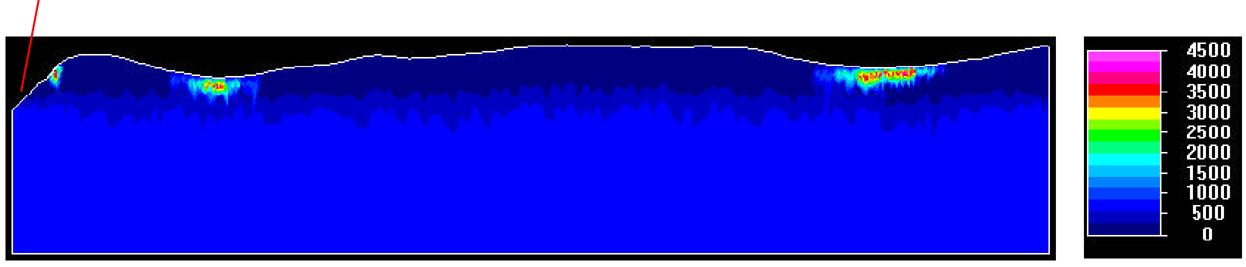
E



Initial head distribution assumes a flat elevated watertable that would be typical of spring conditions. Water is very near or at the surface in the low areas dominated by Ludden and Lamoure soils..

Solute Concentration

F



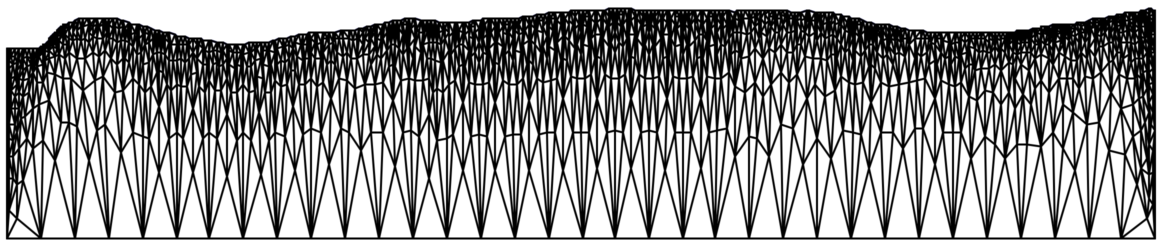
Solute concentrations associated with low abandoned meanders was based on EM-38 and soil survey data typical of soils in this hydrogeologic setting. The highest salinity is associated with the poorly drained Ludden and Lamoure soils. Lowest salinity is associated with the moderately well drained Ladelle soil. Underlying substrate alluvium was give an initial concentration of 500 units.

In order to investigate intrusion of Sheyenne River water into the adjacent soils, the solute concentration of the Sheyenne River water was fixed at 1000 units.

Figure 6. Modeling parameters and initial and boundary conditions for an idealized LaDelle-Ludden-Wahpeton soil association typical of alluvial soils on low floodplains of the Sheyenne river above Lake Ashtabula. Simulation includes high river-water salinity and a higher river stage.

Mesh

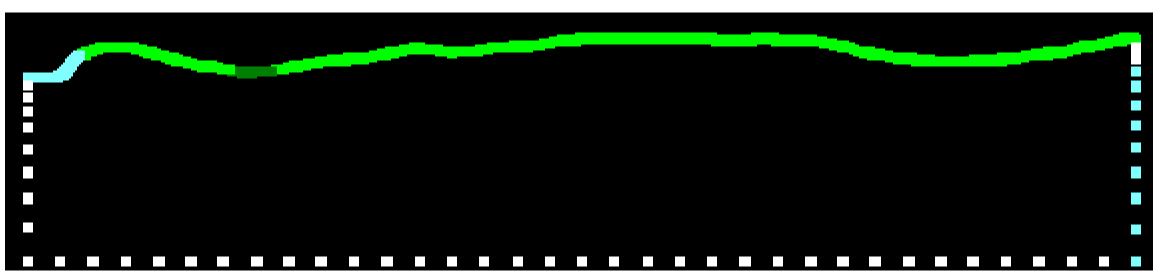
A



Mesh generated in Meshgen for the discritization of initial conditions and running the finite element model. A denser mesh is required near the soil surface where head and concentration gradients are greatest. Cross-section elevations taken from a representative section along the Sheyenne River near the Cooperstown control point.

Boundary Conditions

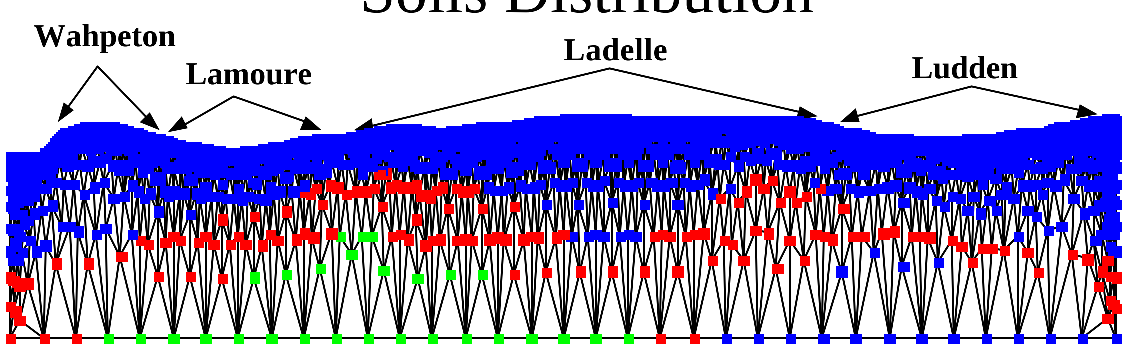
B



Boundary Conditions:
White: No Flow
Green: Atmospheric
Dark Green: Seepage face
Sky Blue: Constant head

Soils Distribution

C

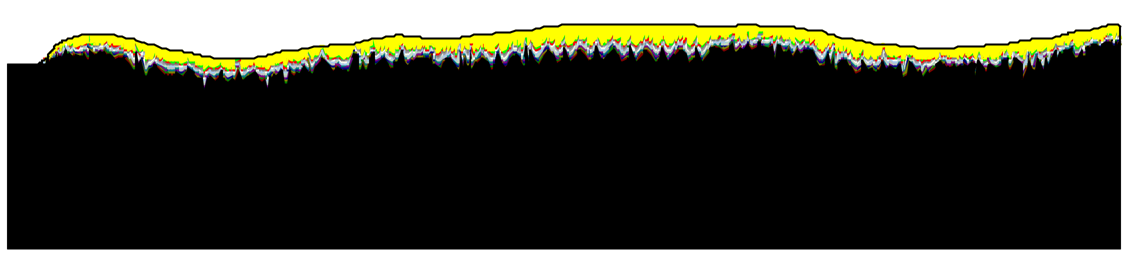


Material Distribution:
Red: Loam
Blue: Silty clay Loam
Green: Clay loam

Note that these alluvial soils consist of moderately well drained to poorly drained fine and medium textured sediments. Soils in the LaDelle-Ludden-Wahpeton association are discussed in section 4.2.2.2 of PEC Report dated January 22, 2002

Roots

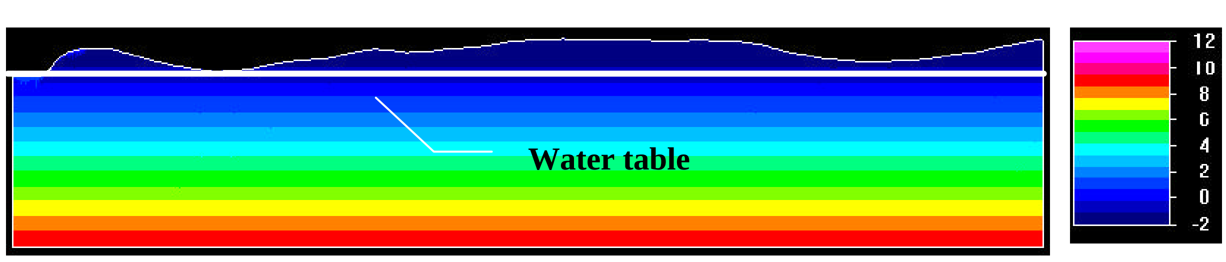
D



Root density (non-black colors) was chosen to be greatest at the surface (yellow), and declining with depth.

Initial Head Distribution

E

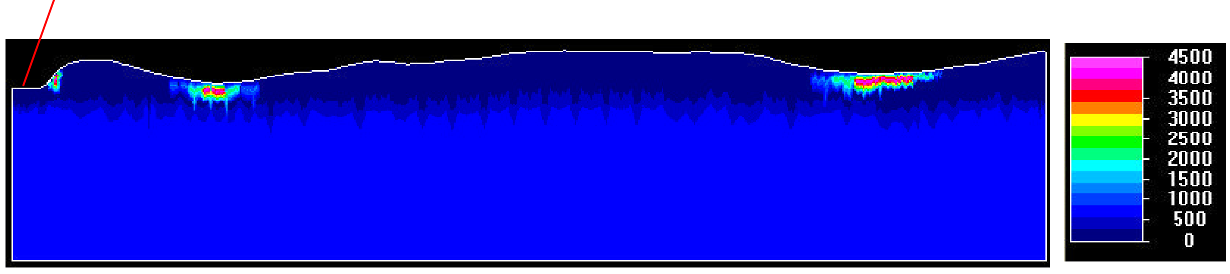


Initial head distribution assumes a flat watertable during spring runoff and flooding. Water is very near the surface in the low areas. Watertables are high to simulate outlet discharge

Sheyenne River
water =3000 units

Solute Concentration

F



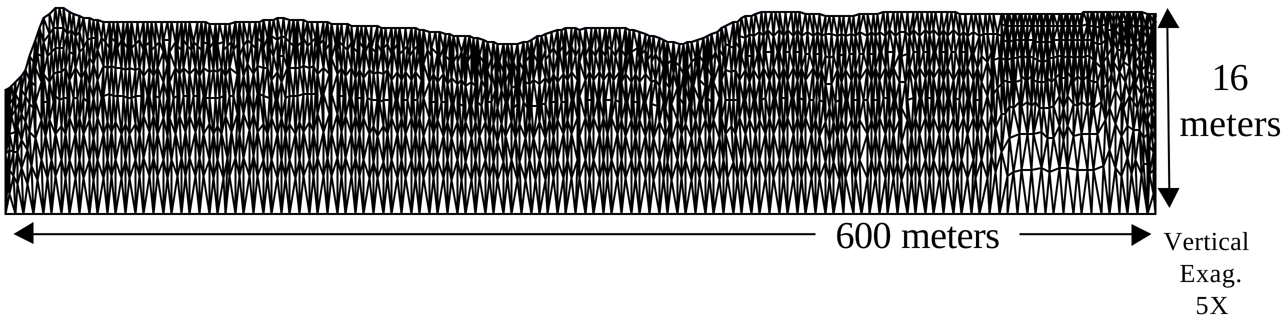
Solute concentrations associated with low abandoned meanders was based on EM-38 and soil survey data typical of soils in this hydrogeologic setting. The highest salinity is associated with the poorly drained Ludden and Lamoure soils. Lowest salinity is associated with the moderately well drained LaDelle soil. Underlying substrate alluvium was give an initial concentration of 500 units.

In order to investigate intrusion of Sheyenne River water into the adjacent soils, the solute concentration of the Sheyenne River water was fixed at 3000 units.

Figure 7. Modeling parameters and initial and boundary conditions for an idealized Fairdale-LaPrairie-LaDelle soil association typical of alluvial soils on floodplains of the entrenched Sheyenne river below Baldhill Dam.

Mesh

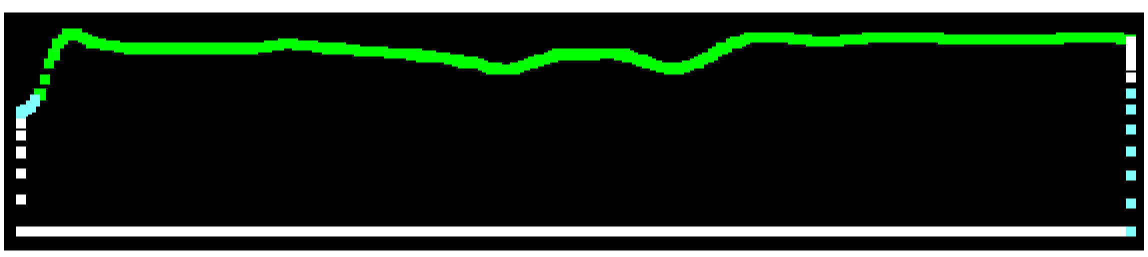
A



Mesh generated in Meshgen for the discritization of initial conditions and running the finite element model. A denser mesh is required near the soil surface where head and concentration gradients are greatest. Cross-section elevations taken from a representative section along the Sheyenne River below Baldhill Dam.

Boundary Conditions

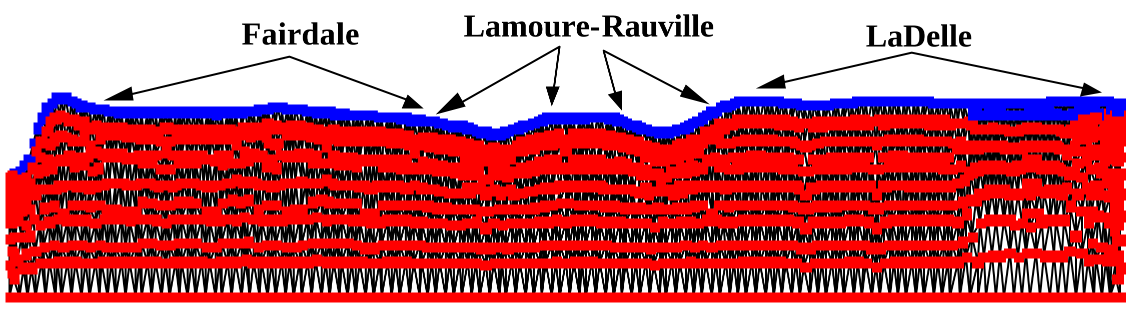
B



Boundary Conditions:
White: No Flow
Green: Atmospheric
Sky Blue: Constant head

Soils Distribution

C

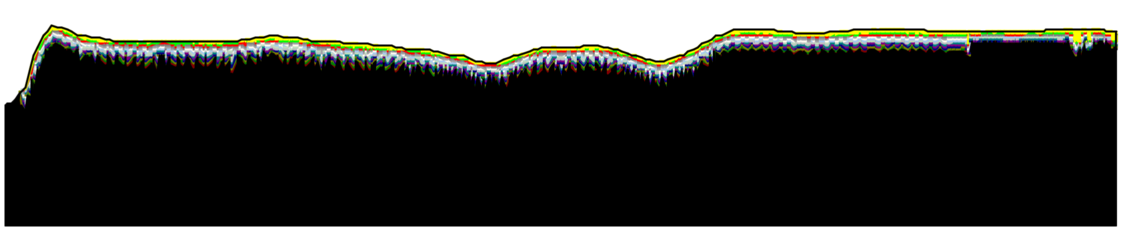


Material Distribution:
Blue: Silty Clay Loam
Red: Clay loam

Note that these alluvial soils consist of moderately well drained and somewhat poor and poorly drained soils in settings where the Sheyenne River is deeply entrenched into the floodplain. The surfaces of the LaDelle and Fairdale soils are well above the normal stage of the Sheyenne River. Typical soils are discussed in section 4.2.2.4 of PEC report dated January 22, 2002.

Roots

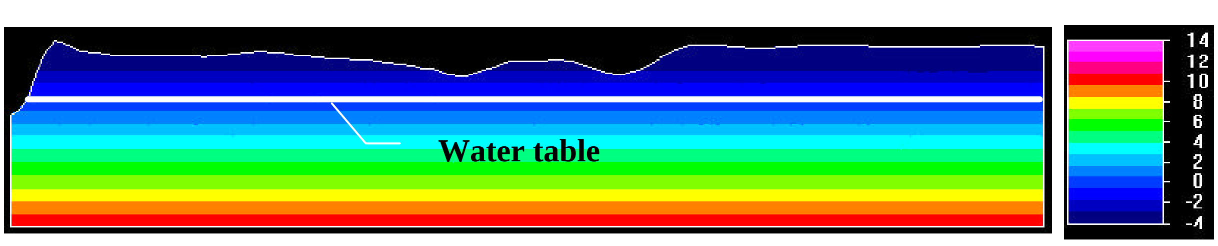
D



Root density (non-black colors) was chosen to be greatest at the surface (yellow), and declining with depth.

Initial Head Distribution

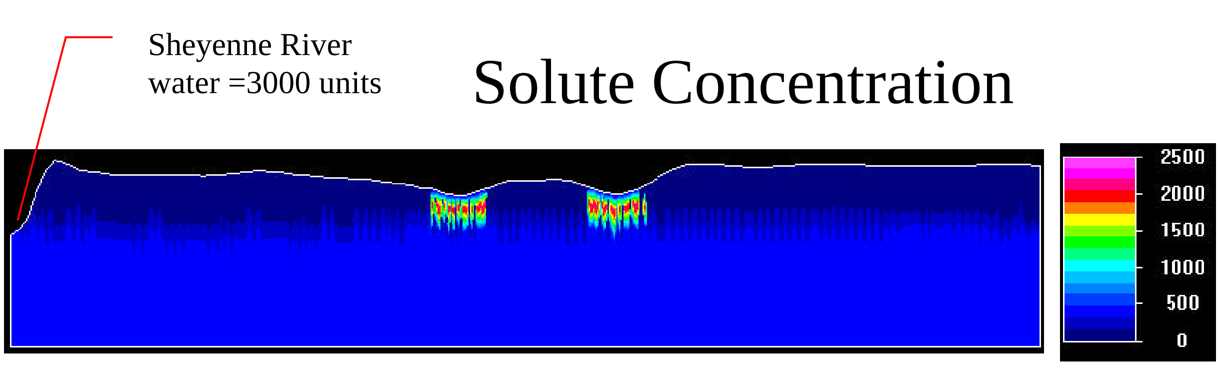
E



Initial head distribution assumes a flat water table characteristic of spring recharge. Water is near the surface in the low areas, relatively deep in moderately well drained positions.

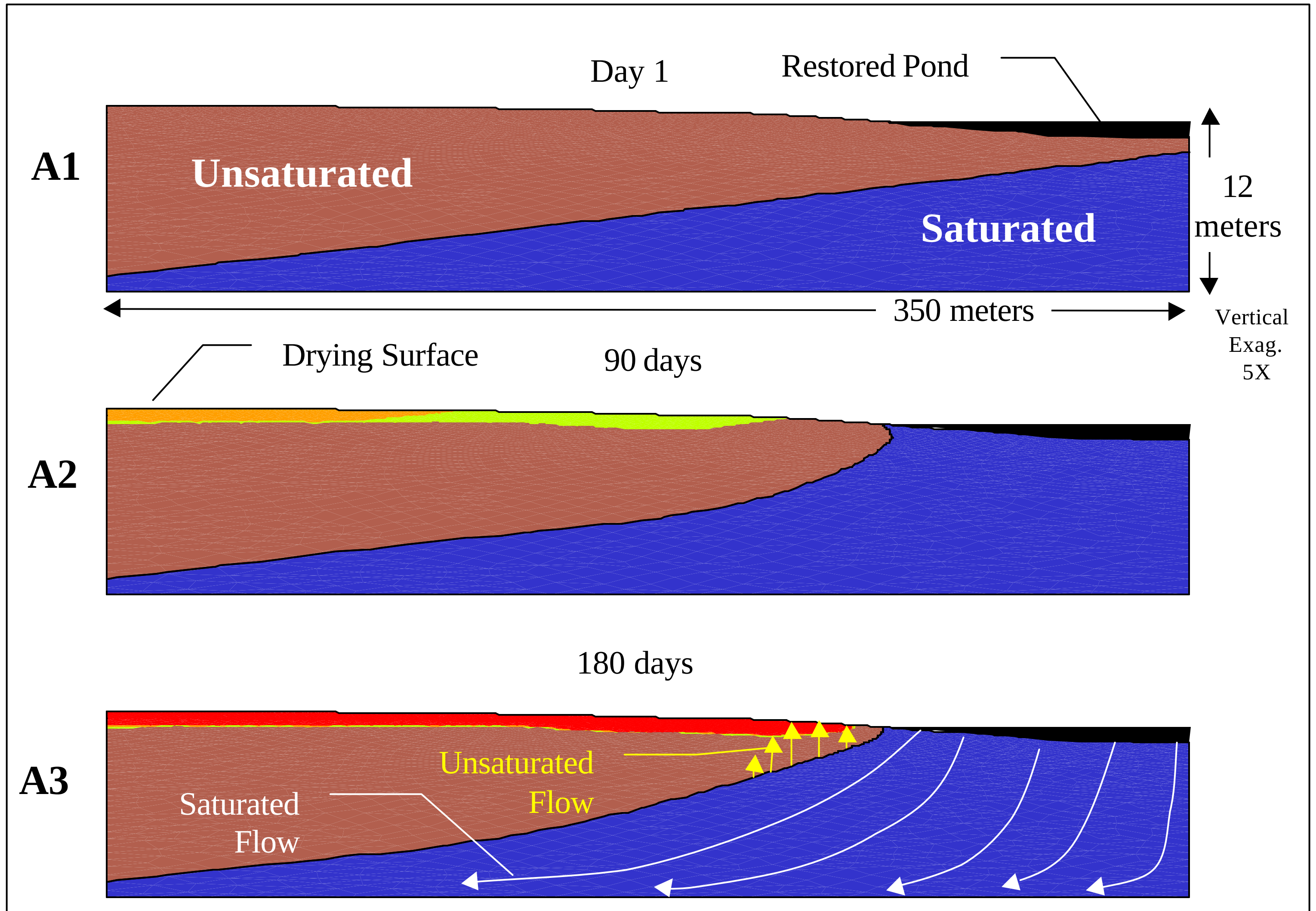
Solute Concentration

F

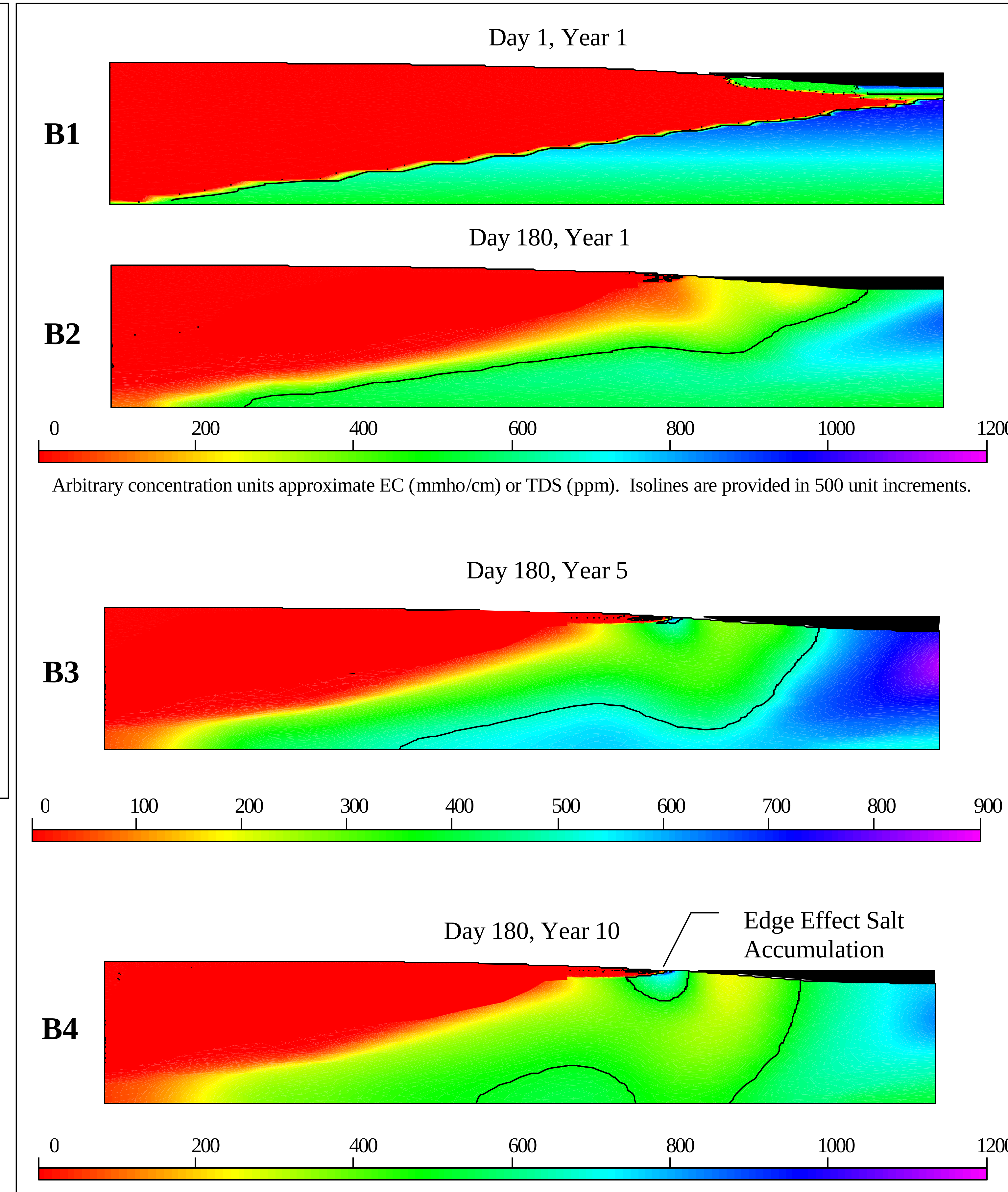


Solute concentrations associated with low abandoned meanders was based on EM-38 and soil survey data and is typical of soils in these positions. Surface soils in upland positions have solute concentrations in the range of 0-250 concentration units. Subsoils we given a concentration of 500 concentration units.

In order to investigate intrusion of Sheyenne River water into the adjacent soils, the solute concentration of the Sheyenne River water was fixed at 3000 units.



A. Watertable configuration and saturation dynamics

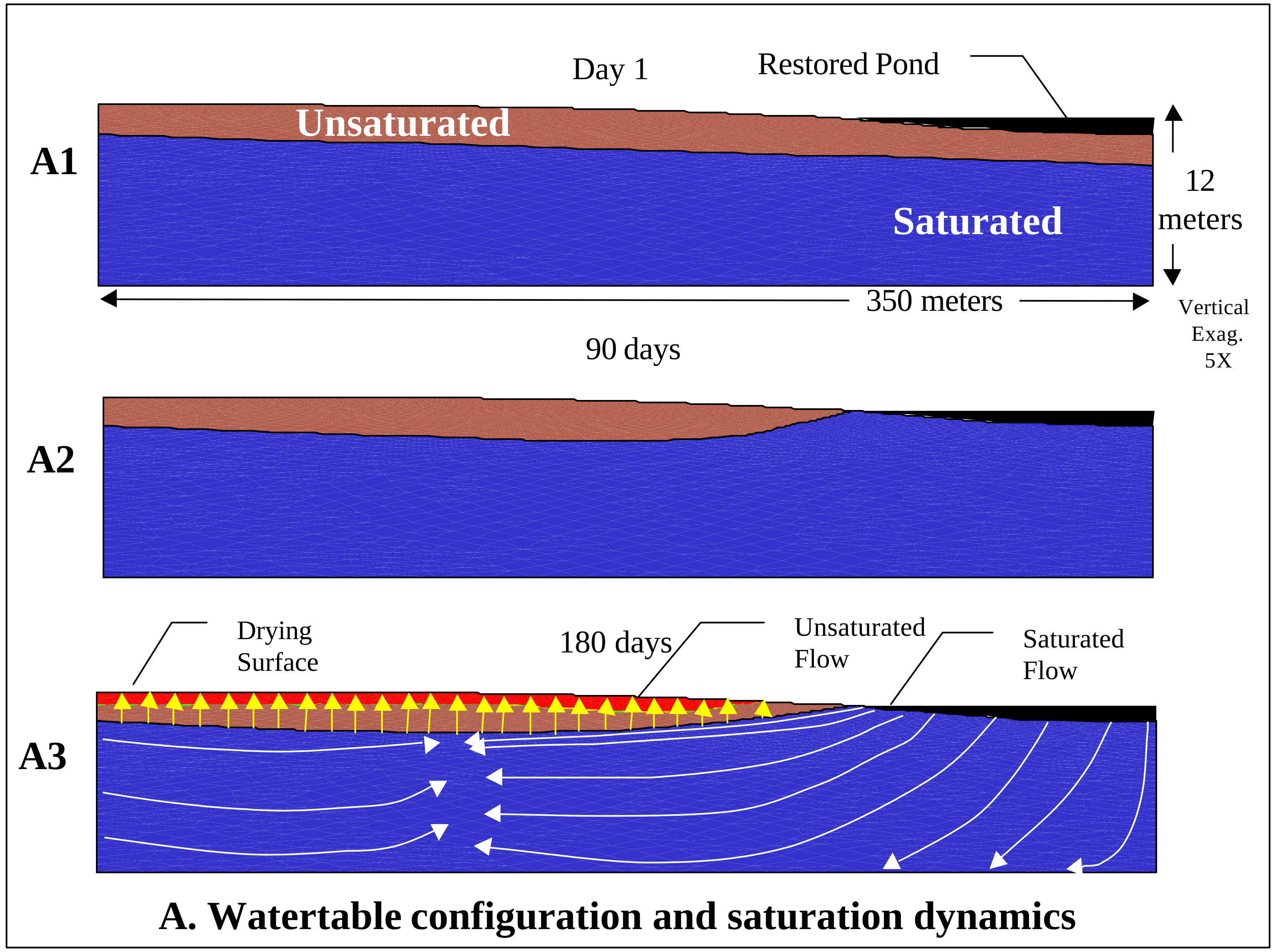


B. Salinity distribution, model years 1, 5, and 10

Figure 8. Simulated watertable configuration, saturation dynamics, and salinity distribution associated with an idealized Upper Basin recharge wetland dominated by Tonka and Hamerly soils, with Svea soils in the upland.

A. Flowlines in A3 have been added to show the dominant direction of saturated and unsaturated flow. The model assumes ditch drainage has removed the surface water component of the wetland, which under drained conditions would still be characterized by a high water table during spring and early summer. Restoration under the model assumes that the pond will persist through the growing season, and then will draw down during fall and winter to approximate initial spring runoff conditions. Spring snowmelt and runoff would then rstore the pond. Note the growth of the dry surface throughout the model period.

B. The model assumes a 180 day growing season. In order to simplify the model, a realistic, net-negative precipitation /evapotranspiration ratio has been assumed. Salinity distribution at time zero is typical of drained recharge-type wetlands. Over time the restoration results in a mobilization of dissolved salt away from the pond and to the restored pond edge. However, the net downward movement of saturated flow results in a freshening of the pond sediments. Because the majority of salts are leached downward, salt accumulations at the pond edge are minor. Adjacent cropland with a deep water table is not significantly affected by salinization because the water table is below the depth necessary to result in significant unsaturated flow of water from the water table to the soil surface. Restoration of similar recharge ponds would have no salinization hazards for adjacent cropland.



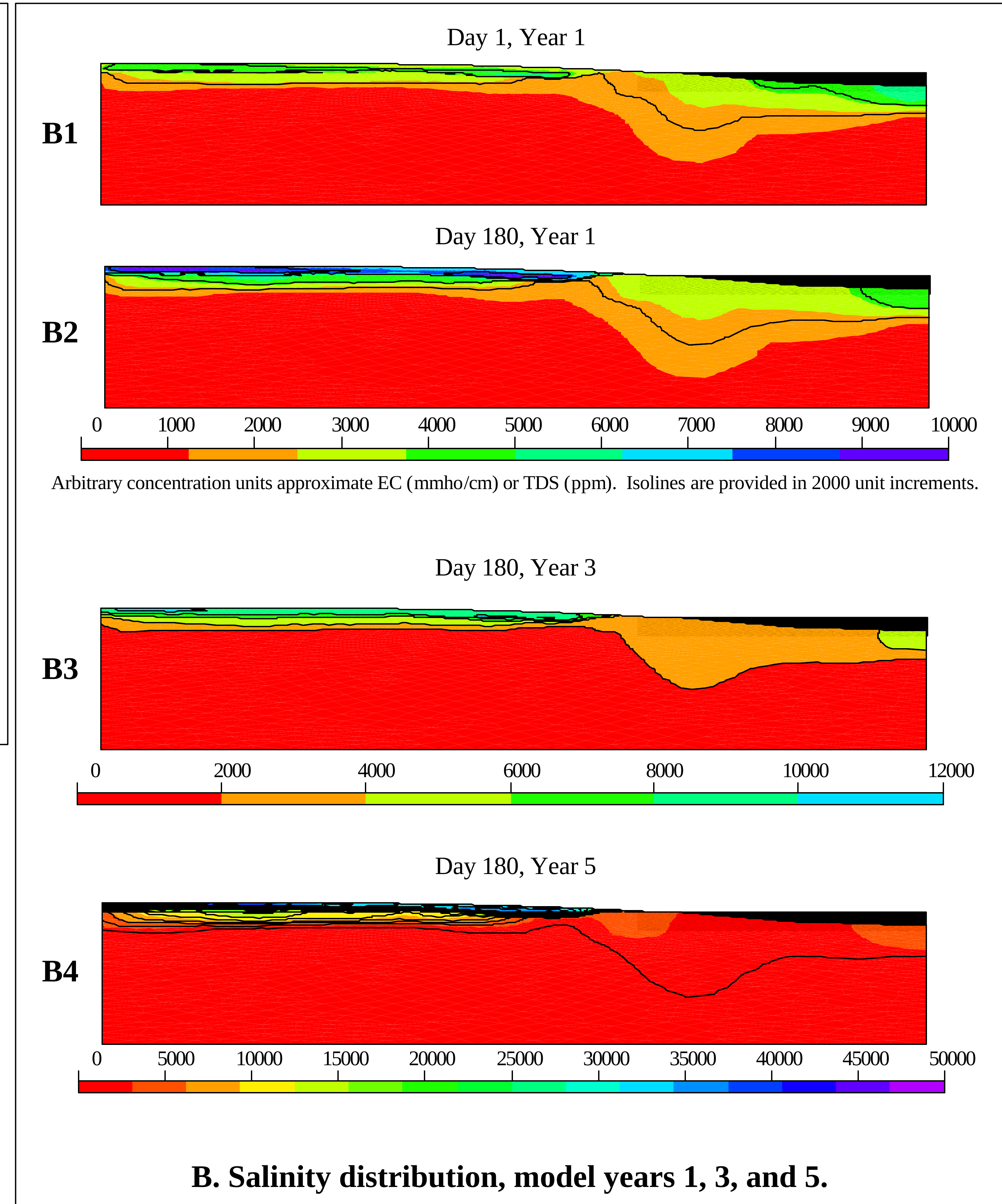


Figure 9. Simulated water table configuration, saturation dynamics, and salinity distribution associated with an idealized, restored Upper Basin discharge-wetland dominated by Hegne and Hamerly soils.

A. Flowlines in A3 have been added to show the dominant direction of saturated and unsaturated flow after restoration. The model assumes that ditch drainage has removed the surface water component of the wetland, which under drained conditions would still be characterized by a high water table. Initial conditions assume that salts accumulate near the ditch and in and near the historic wetland soil surface. Restoration assumes that the pond will persist throughout the year. The low hydraulic gradient typical of low-relief areas around discharge wetlands is reflected in a generally high water table throughout the section. Low hydraulic gradients result in slow water movement except in the coarse-textured sandy loam material that can transport substantial amounts of water under low hydraulic gradients. Note the growth of the dry surface above the sand stringer. The sandy loam lens that was above the water table under drained conditions is saturated under restored conditions and can act as a conduit for brackish water, which can then be drawn to the surface by unsaturated flow.

B. The model assumes a 180-day growing season. In order to simplify the model, a realistic, net-negative precipitation /evapotranspiration ratio has been assumed. Salinity distribution at time zero represents an idealized, drained discharge-type wetland with adjacent, moderately saline, somewhat poorly drained soils. Over time, the restoration results in salt mobilization away from the pond to the restored pond edge and from the subsoil to the soil surface, especially noticeable above the sand stringer that is saturated under restored conditions. After 5 years the model predicts surficial salt concentrations to a maximum of 40 dS/m. Adjacent cropland would be significantly and adversely be affected by salinization of the surface soil under this situation. Restoration of similar discharge ponds would have significant hazards for adjacent cropland, however, much of the cropland may have existing salt hazards that would be exacerbated by the restoration.

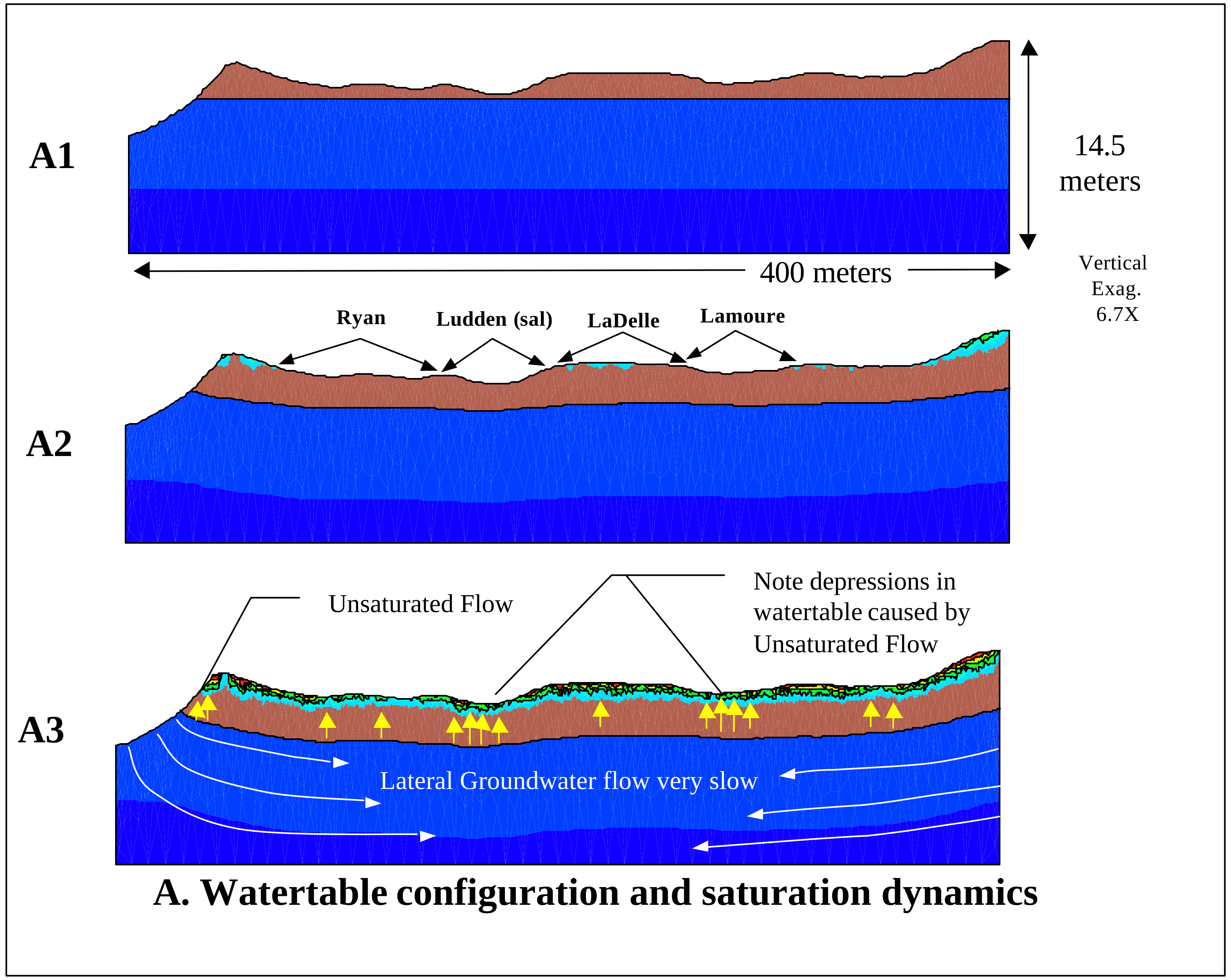
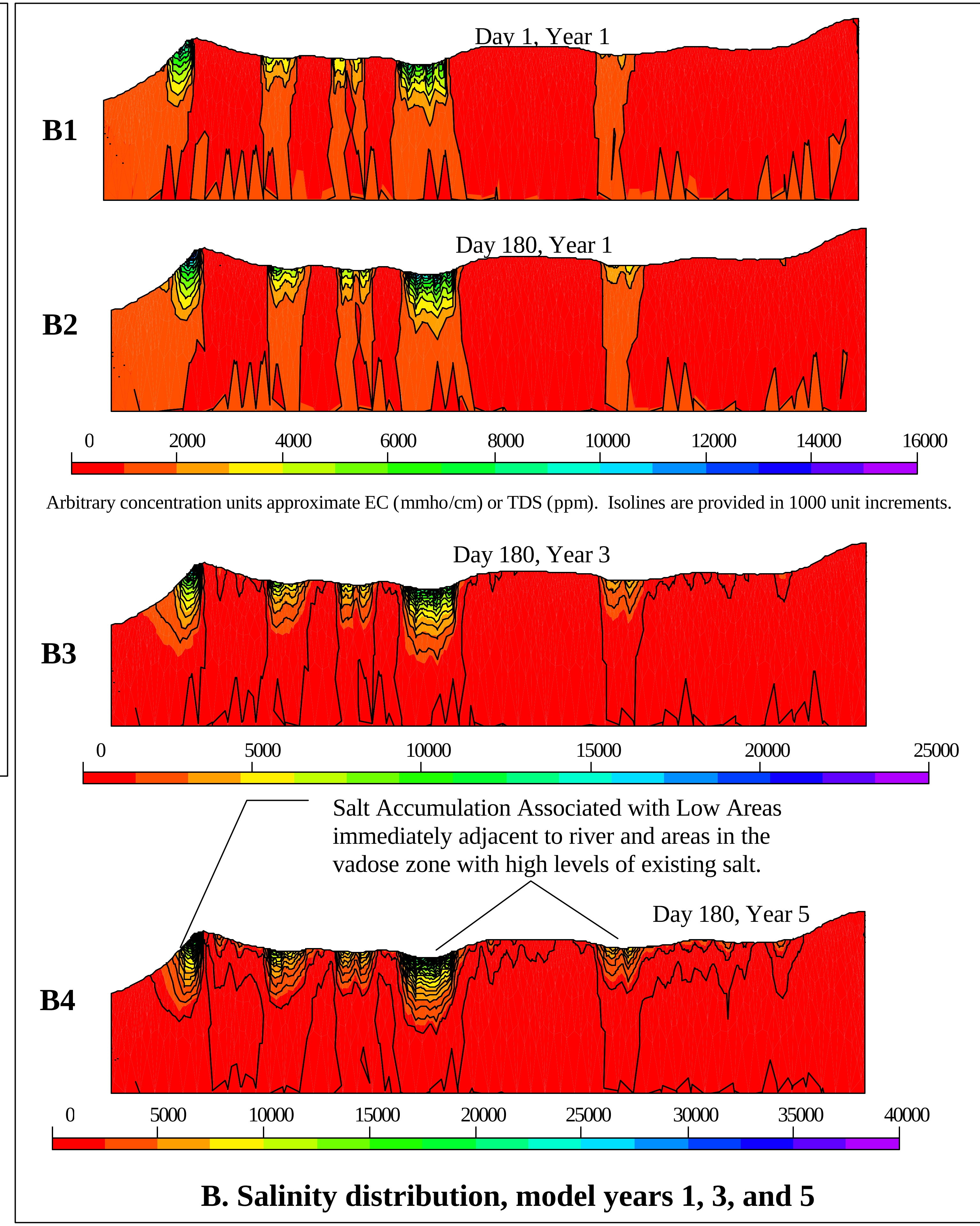
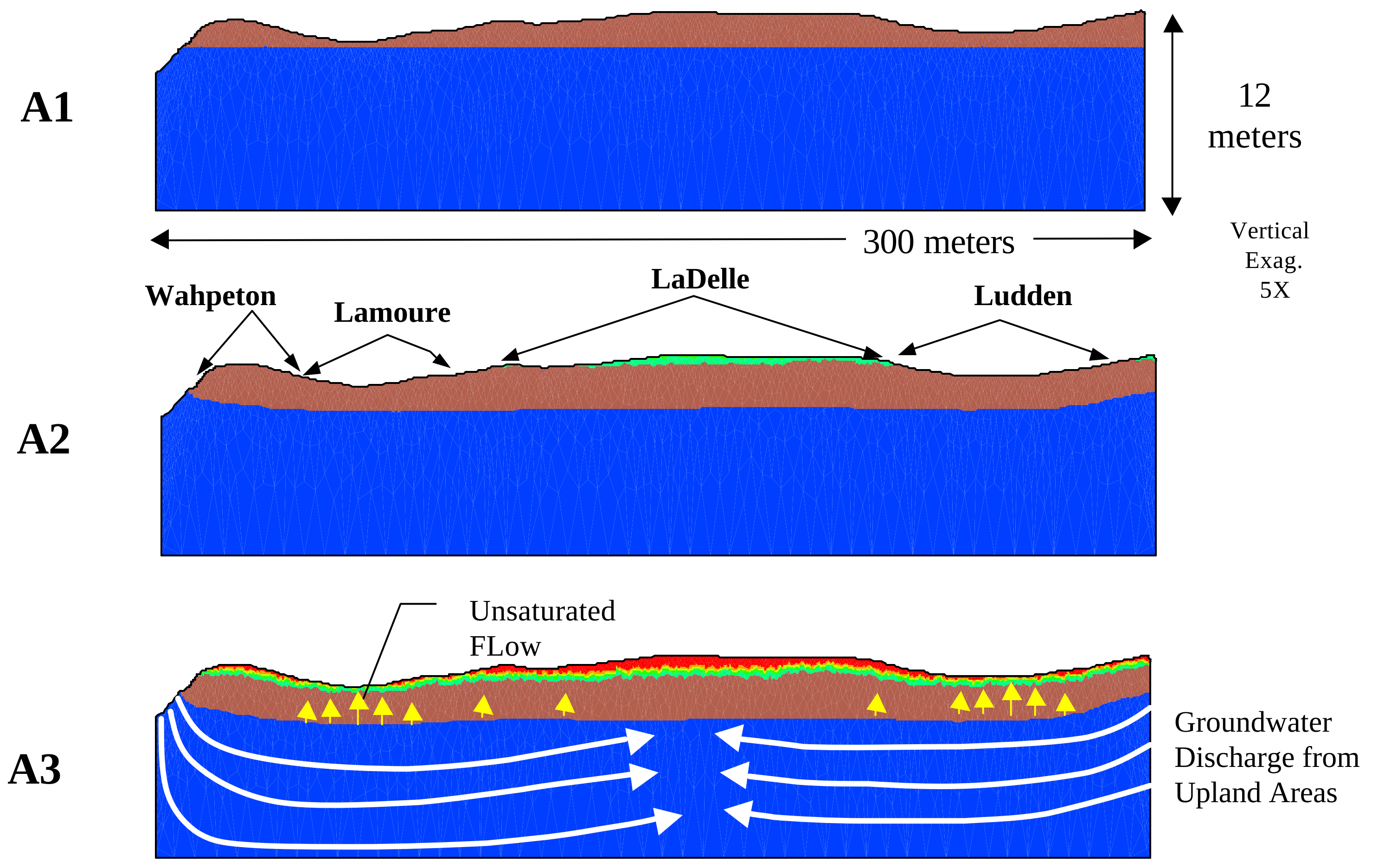


Figure 10. Simulated watertable configuration, saturation dynamics, and salinity distribution associated with an idealized Lamoure-LaDelle-LaPrairie-Ryan soil association typical of fine-textured alluvial soils on low floodplains of the upper reaches of the Sheyenne River above Lake Ashtabula.

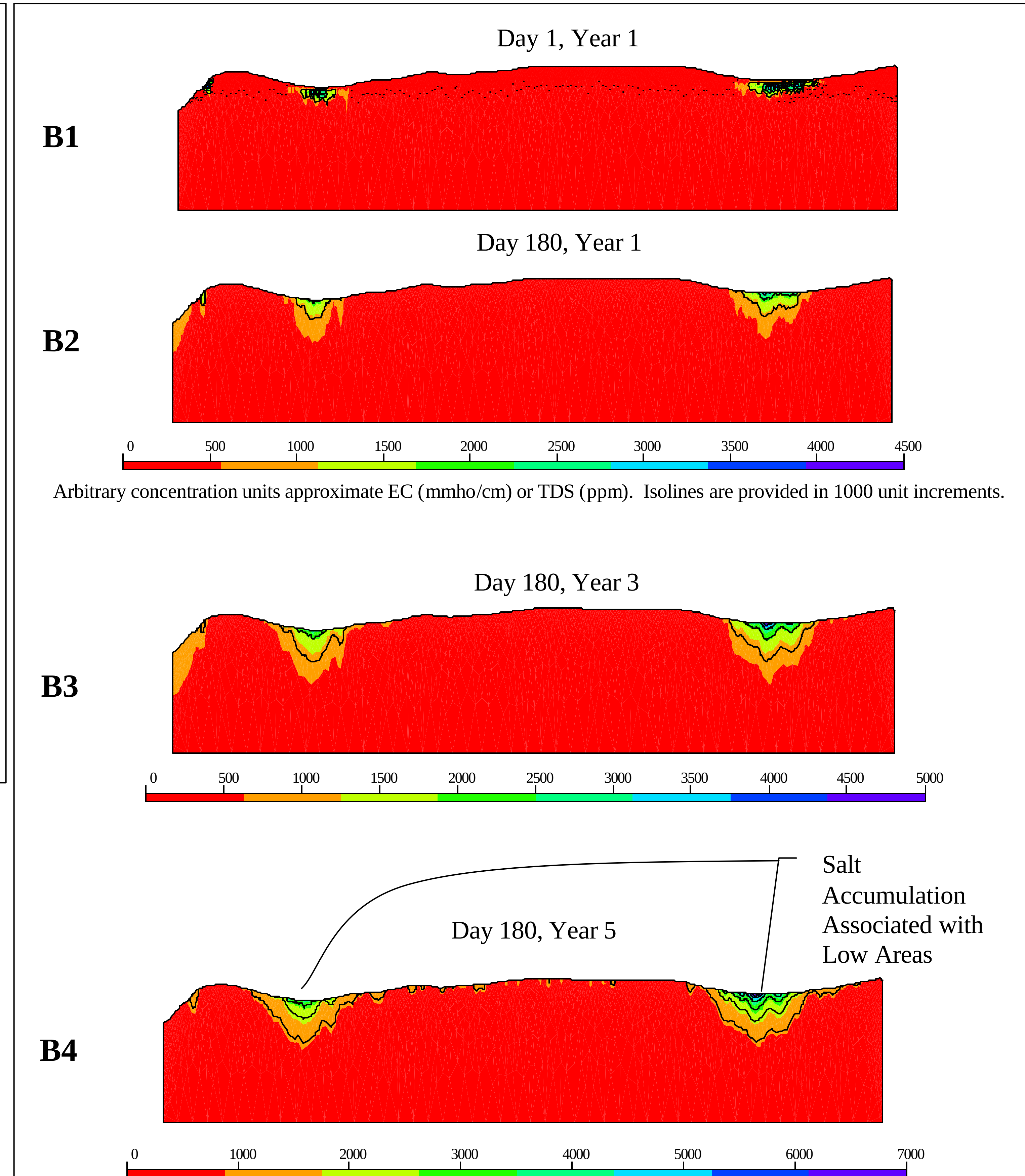
A. Unsaturated and saturated groundwater flowlines in A3 have been added to show the dominant direction of saturated and unsaturated flow. The stage of the Sheyenne River remains constant at the spring level. Note that because of the low hydraulic conductivity of the alluvium, evapotranspiration removes more water over the growing season than can be replaced by groundwater movement, resulting in a dramatic decline in the watertable. Note the growth of the dry surface throughout the model period, the decline in water table elevation to below river stage, and the development of groundwater depressions under land surface depressions.

B. The model assumes a 180 day growing season. In order to simplify the model, a realistic, net-negative precipitation /evapotranspiration ratio has been assumed. Salinity distribution at time zero is typical of Ryan, Ludden, Lamoure, and LaDelle soils. Note the increase in soil salinity associated with the depressional positions occupied by Ludden, Ryan, and Lamoure soils resulting from high initial levels of salinity coupled with evapotranspiration drawing water from shallow watertables and concentrating the salts in and near the rooting zone. At the end of the 5-year modeling period, some salinization associated with the moderately well drained LaDelle soils can be observed, however, not to levels that would result in significant crop affects. LaDelle soils are more subject to salinization under conditions where water tables are persistently shallow.





A. Watertable configuration and saturation dynamics

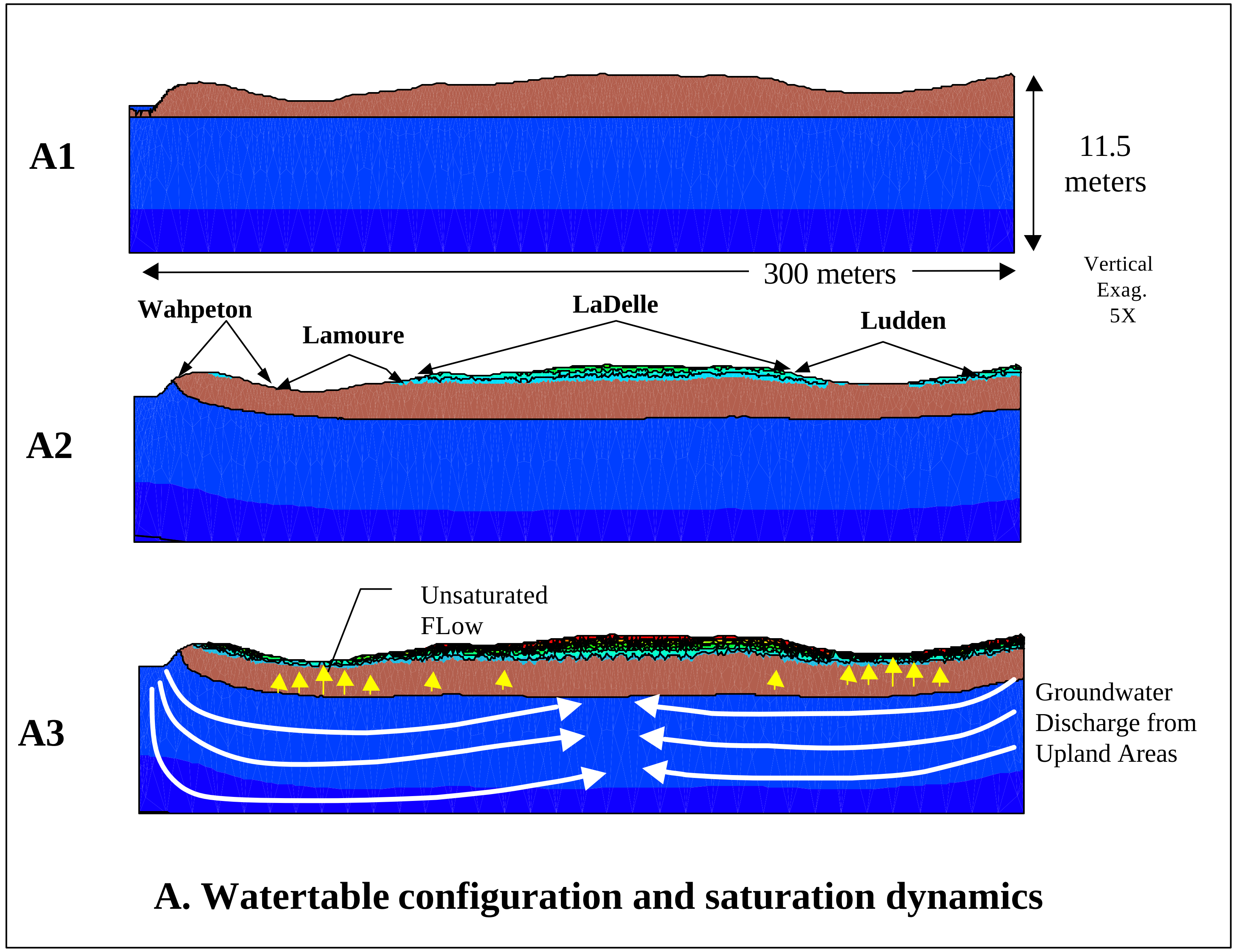


B. Salinity distribution, model years 1, 3, and 5

Figure 11. Simulated watertable configuration, saturation dynamics, and salinity distribution associated with an idealized LaDelle-Ludden-Wahpeton soil association typical of alluvial soils on low floodplains of the Sheyenne river above Lake Ashtabula.

A. Flowlines in A3 have been added to show the dominant direction of saturated and unsaturated flow. The stage of the Sheyenne River remains constant at the spring level. Note that because of the low hydraulic conductivity of the alluvium, evapotranspiration removes more water over the growing season than can be replaced by groundwater movement, resulting in a dramatic decline in the water table. Note the growth of the dry surface throughout the model period, the decline in water table elevation to below river stage, and the development of groundwater depressions under land surface depressions.

B. The model assumes a 180 day growing season. In order to simplify the model, a realistic, net-negative precipitation /evapotranspiration ratio has been assumed. Salinity distribution at time zero is typical of LaDelle, Ludden and Wahpeton. Note the increase in soil salinity associated with the depressional positions occupied by Ludden and Lamoure soils resulting from diffusion of relatively high initial levels of salinity coupled with evapotranspiration drawing water from shallow watertables and concentrating the salts in and near the rooting zone over the growing season. Note also that intrusion of Sheyenne River water into the adjacent soils is limited due to the low hydraulic gradients present under this modeling simulation. At the end of the 5-year modeling period, some minor salinization associated with the moderately well drained LaDelle soils can be observed, however, not to levels that would result in significant crop affects. If subsoil salinity were higher under the LaDelle soils, they would be more subject to salinization because the water table under this scenario is persistently shallow.



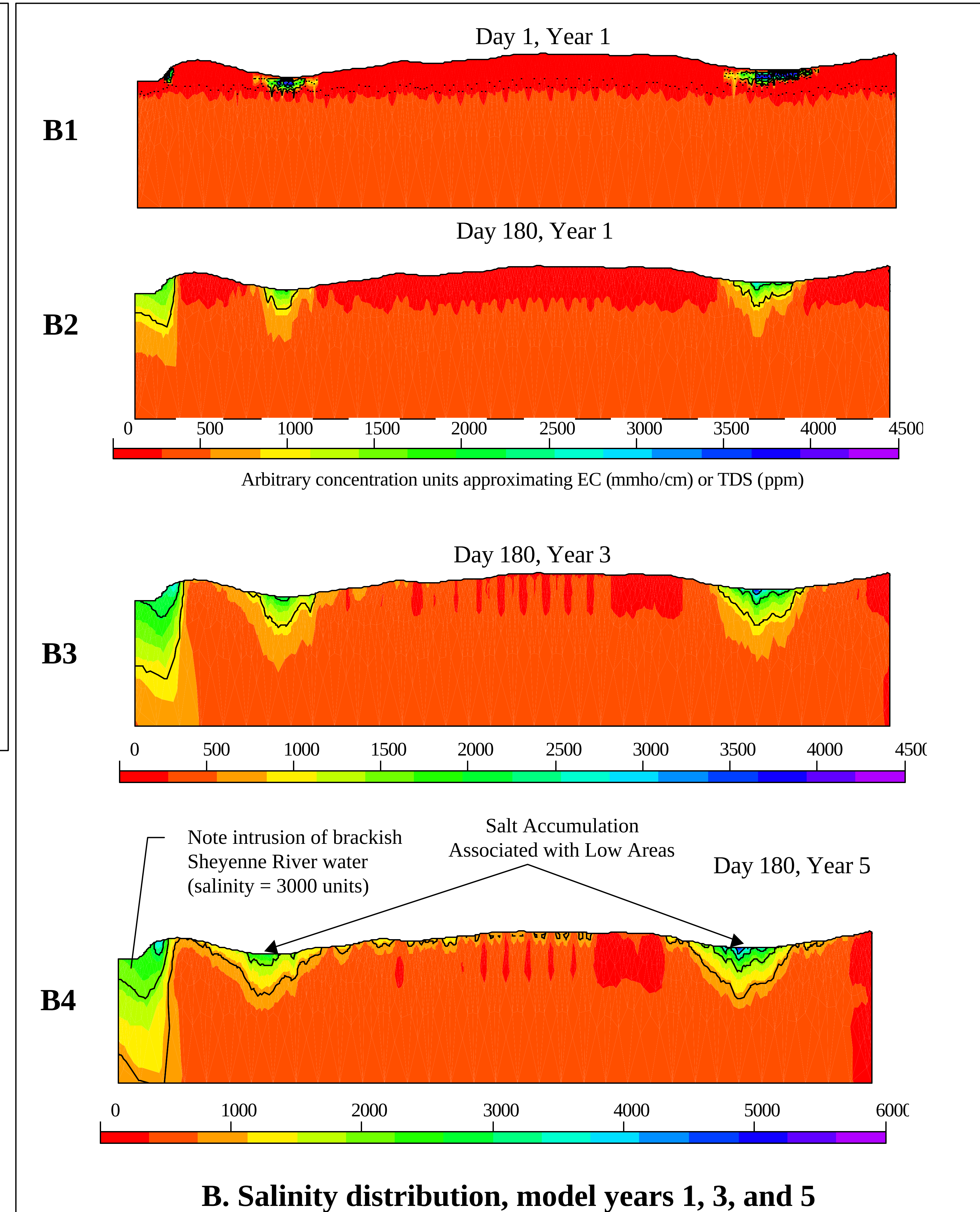
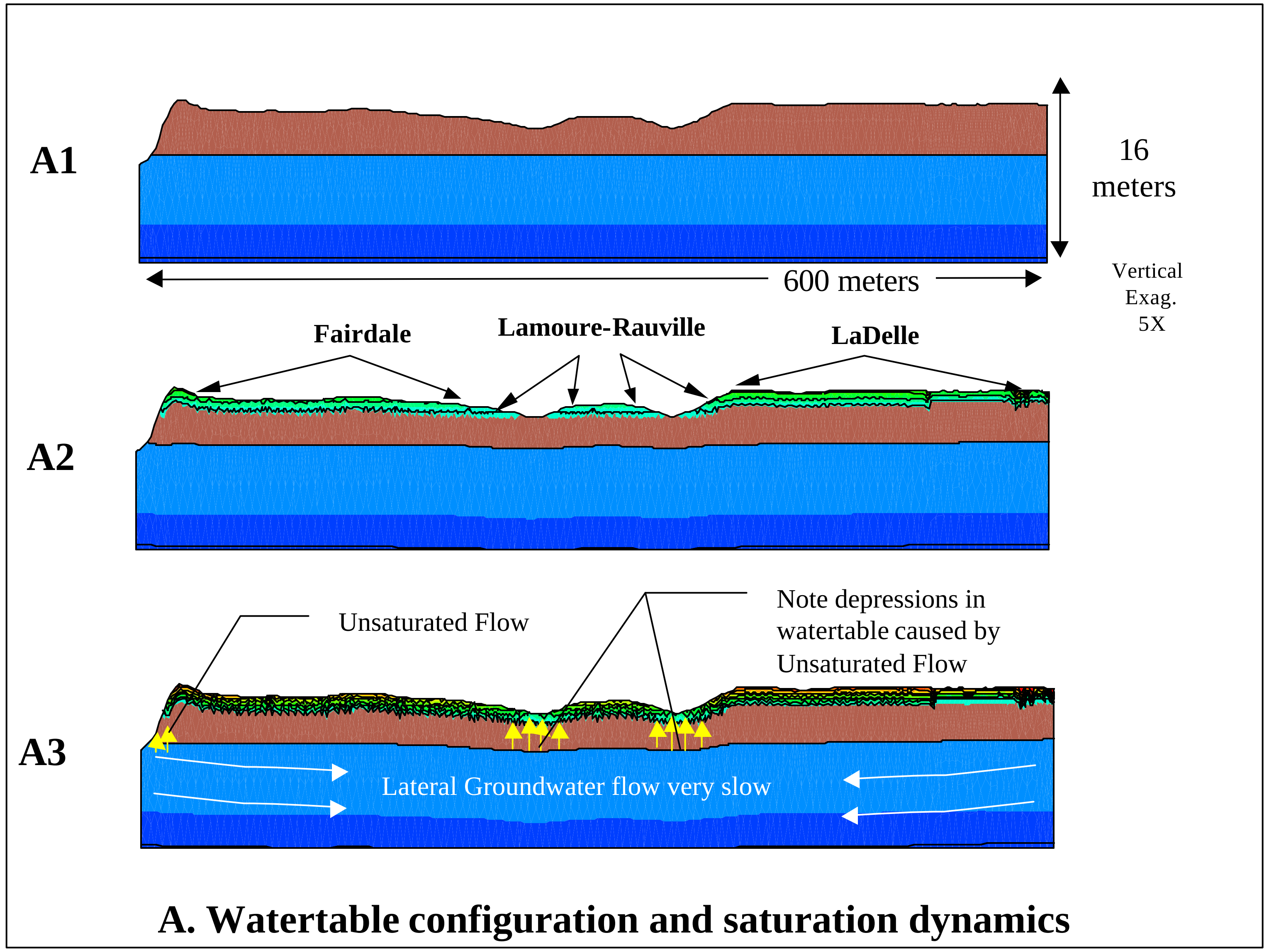


Figure 12. Simulated water table configuration, saturation dynamics, and salinity distribution associated with an idealized LaDelle-Ludden-Wahpeton soil association typical of alluvial soils on low floodplains of the Sheyenne river above Lake Ashtabula. Simulation includes high river-water salinity and a higher river stage.

A. Compare to Figure 9 which shows the same setting under lower river stages and river water salinity. Flowlines in A3 have been added to show the dominant direction of saturated and unsaturated flow. The stage of the Sheyenne River remains constant at an increased spring level when compared to Figure 9. Note that evapotranspiration still removes more water over the growing season than can be replaced by groundwater movement in spite of the increased stage. resulting in a significant head gradient away from the river. Note the growth of the dry surface throughout the model period, the decline in water table elevation to well below river stage, and the development of groundwater depressions under land surface depressions.

B. The model assumes a 180 day growing season. In order to simplify the model, a realistic, net-negative precipitation /evapotranspiration ratio has been assumed. Salinity distribution at time zero is typical of LaDelle, Ludden and Wahpeton. The increase in soil salinity associated with the depressional positions occupied by Ludden and Lamoure soils is similar to that seen in Figure 9. The development of soil salinity associated with positions away from the river is similar to that seen in Figure 9 as well. However, note that salinization due to the intrusion of Sheyenne River water is now significant in adjacent soils due to the large hydraulic gradients present near the river under this modeling simulation.. However, soil salinization is confined to the areas immediately next to the river because hydraulic gradients are low and the hydraulic conductivity of the sediments is not great.



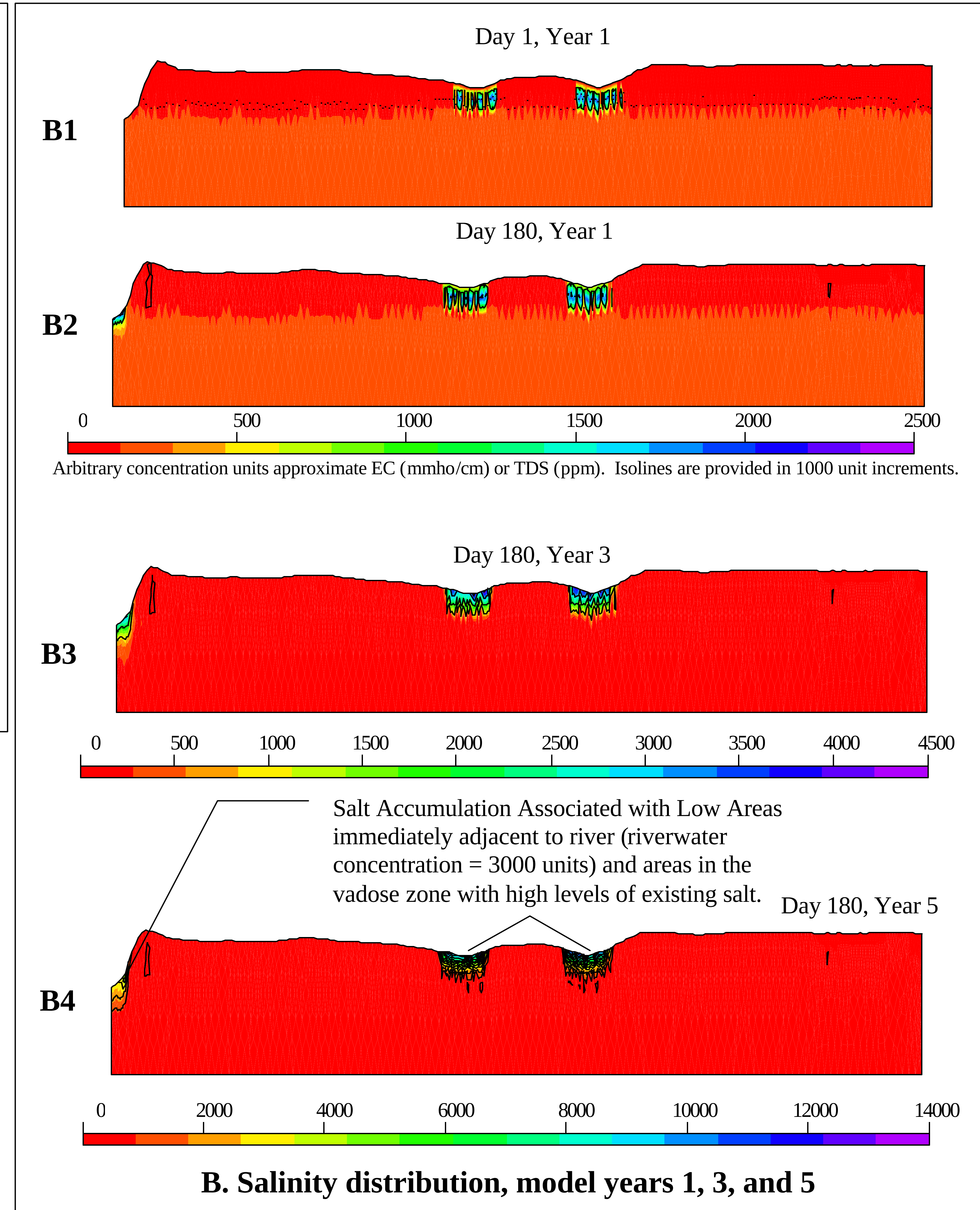


Figure 13. Simulated water table configuration, saturation dynamics, and salinity distribution associated with an idealized Fairdale-LaPrairie-LaDelle soil association typical of alluvial soils on floodplains of the entrenched Sheyenne river below Baldhill Dam.

A. Flowlines in A3 have been added to show the dominant direction of saturated and unsaturated flow. Note the growth of the dry surface throughout the model period. The stage of the Sheyenne River remains constant at the spring level. Note that because the depth to the water table is generally deep across the section, evapotranspiration is not a significant factor in lowering the water table. This results in a generally flat water table with slight depressions under the wetlands where limited evapotranspirative withdrawal of water does occur. Note the growth of the dry surface throughout the model period, and the development of slight groundwater depressions under land surface depressions

B. The model assumes a 180 day growing season. In order to simplify the model, a realistic, net-negative precipitation /evapotranspiration ratio has been assumed. Salinity distribution at time zero is typical of Fairdale, LaDelle, Lamoure, and Rauville soils on the elevated terrace above the entrenched Sheyenne River. Note that little change in soil salinity is associated with the moderately drained upland soils. At the end of the 5-year modeling period, some minor salinization associated with the somewhat poor and poorly drained Lamoure and Rauville soils can be observed. However, salinization of the moderately well drained Fairdale and LaDelle soils is not a significant factor after 5 years. Note also that intrusion of Sheyenne River water into the adjacent soils is very limited due to the low hydraulic gradients present under this modeling simulation.

Appendix A

Appendix A

The Effects of Gypsum on Soil Salinization Processes

1. BACKGROUND

Most saline soils in North Dakota contain gypsum to greater or lesser degrees. Gypsum is a sparingly soluble salt whose solubility in pure water is approximately 2 grams per liter. The presence of gypsum can increase the salinization hazard of soils subjected to salt mobilization because calcium ions released as gypsum dissolves are preferentially adsorbed on the cation exchange complex, replacing exchangeable Mg and Na (Bresler et al., 1982). The Mg and Na ions thus mobilized add to the salt load in the groundwater. Charge balance is maintained by sulfate (SO_4^{2-}) ions also released by gypsum dissolution (Equation 1).

$$2CaSO_4.2H_20 = \cancel{2Ca^{2+}} + 2SO_4^{2-}$$

$$\cancel{2Ca^{2+}} + Na_2Mg\text{-[Soil Clay]} = 2Na^+ + Mg^{2+} + 2Ca\text{-[Soil Clay]}$$

Equation 1 $$CaSO_4.2H_2O + Na_2Mg\text{-[Soil Clay]} = 2Na^+ + Mg^{2+} + 2SO_4^{2-} + 2Ca\text{-[Soil Clay]}$$

Thus the soil cation exchange complex, consisting of positively charged cations adsorbed to the negatively charged surface of soil clays, acts as an additional source of soluble salts. The result is that the pattern of movement of soluble ions with time in gypsiferous soils can represent a “constant-source/constant composition” scenario as opposed to a simple “flushing” of soluble ions from one place to another. The effects may or may not be significant depending on texture, cation exchange capacity (CEC), and exchangeable cation composition.

The exchange complex in fine-textured soils especially can represent several grams of potential solute per kilogram of soils. Because fine-textured soils have CEC values that can range up to 400-600 mmol of charge per kilogram of soil (mmol(p+)/kg), fine textured soils have a much larger “salinity buffer” as cation exchange when compared to coarse textured soils which range in CEC from 50-200 mmol(p+)/kg soil. However, the cumulative amount of water flowing through fine textured soils is reduced by the low hydraulic conductivity and can mitigate the increased salinization hazard in the short term.

A simple column leaching study was performed using UNSATCHEM software developed by the National Soil Salinity Laboratory (NSSL) to visualize the effects that gypsum has on increasing the amount of salinity that a given volume of soil can release. The UNSATCHEM program numerically solves the Richards' equation for variably-saturated water flow and convection-dispersion type equations for heat, carbon dioxide and solute transport. Further details regarding the program can be found in Appendix B. The program is extensively documented (Simunek et al., 1996; van Genuchten and Simunek, 2000) and is freely available from the NSSL at the following url.

http://www.ussl.ars.usda.gov/MODELS/unsatchm.htm

2. METHODS

The UNSATCHEM program was used to simulate the time-dependent effects of leaching a soil column containing brackish porewater saturated with respect to gypsum with dilute solution equivalent to relatively fresh, non-saline runoff water. Selected physical and chemical features of the simulations are in **Figure 1**.

The following initial and boundary conditions were used for two simulation runs each for uniform columns of loam and a clay loam soil, respectively. The only difference between simulation runs was the inclusion of 500 mmol gypsum/kg soil for the second run.

- The length of the soil column was 1-meter, discritized into 101 nodes with a denser mesh at the surface of the profile where chemical and head gradients are greatest.
- Water flow boundary conditions included a 10-cm constant head boundary at the top surface and free drainage at the bottom surface.
- Initial hydraulic head values were set at +10 cm at the surface grading linearly to 0 cm at the base.
- The columns were completely saturated at time 0. Continuous saturation was maintained throughout the simulations.
- 500 mmol/kg calcite ($CaCO_3$) was assumed for both runs. A kinetic model (opposed to an equilibrium model) was used to incorporate calcite and gypsum precipitation/dissolution into the model.
- Default hydraulic parameters for a loam and a clay loam soil were used. The defaults were calculated within UNSATCHEM (see Appendix B).
- Suggested default iteration criteria and solute transport parameters were used.
- CEC and initial exchangeable cation compositions were as indicated in **Table 1**.
- Initial leaching water and porewater composition was maintained at concentrations indicated in **Table 2**. The chemical composition of the leaching solution is typical of fresh pondwaters from recharge type wetlands. The porewater composition is typical of soil saturation extracts from brackish/subsaline wetlands with gypsiferous sediments. Data were adapted from Arndt, 1987.

3. RESULTS AND DISCUSSION

The UNSATCHEM program provides results in graphical and tabular format. The effects of gypsum on porewater solute concentrations with time are illustrated with simulated solute concentrations plotted as a function of model run time and profile depth. The results are analogous to the mobilization of salts by leaching resulting from the wetland restoration or flooding. The results of the simulations are provided along with a discussion for the loam soil and the clay loam soil in **Figures 2 and 3**, respectively. The reader is directed to these figures for a discussion of the effects of gypsum on solute concentration and salt mobilization in soils undergoing leaching with dilute solutions.

4. CONCLUSIONS AND IMPLICATIONS FOR MODELING AND INTERPRETING SALINIZATION PROCESSES IN NORTH DAKOTA

Gypsum is a common constituent of saline North Dakota soils. The effects of gypsum dissolution on salinization processes are illustrated through column leaching simulations of gypsiferous and non-gypsiferous loam and clay loam soils using UNSATCHEM software. The results indicate that the presence of gypsum results in an additional salt load produced by the replacement of adsorbed cations by calcium released by gypsum dissolution. While the total amount of additional salt is greater with fine-textured soils due to greater total concentrations of adsorbed cations, the effects are mitigated to a large degree by the lower hydraulic conductivity of fine textured soils.

For the purposes of modeling salinization processes along the Sheyenne River and in Upper Basin wetlands it was assumed that salinity could be modeled using electrical conductivity (EC) or total dissolved solids (TDS) as a single-constituent, non-reactive surrogate for salinity. While this assumption is appropriate to illustrate salinization processes, the UNSATCHEM modeling of the effects of gypsum indicates that detailed, predictive modeling of salinization processes must include the effects of gypsum. The resulting modeling effort necessary to accurately predict salinization processes with time would be complicated by the requirement that all major solute constituents be included in the model. The resulting modeling complexity combined with the heterogeneity inherent in soil chemical and physical features and soil gypsum contents would limit the applicability of large-scale modeling of salinization processes.

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Appendix A

Tables

Table 1. CEC and exchangeable cations used for all simulations. Data are typical of CECs and exchangeable cation distribution in loam and clay loam soils of brackish to saline wetlands in North Dakota (adapted from Arndt, 1987).

Soil	CEC[1]	Exchangeable Cations[2]			
		Ca	Mg	Na	K
	mmol (p+)/kg soil[3]				
Loam	225	100	100	15	10
Clay loam	450	200	200	30	20

1 Cation exchange capacity is determined by replacing the adsorbed cations with an index ion, then replacing the index ion with another ion in a known quantity of solution and determining the concentration of the index ion in the extract.

2 Exchangeable cations are determined by replacing all exchangeable ions with an index ion in a known volume of solution, extracting the solution from the soil/solution slurry and then determining the concentration of the original replaced ions in the extract.

3 Concentration units for exchangeable cations are input in the UNSATCHEM program as millimoles of positive charge per kilogram soil (mmol(p+)/kg. Older literature may have these concentrations units as milliequivalents (meq) per unit weight soil.

Table 2. Chemical composition of leaching and porewater solutions used for all simulations. Data are typical of pondwater and porewater solutions in North Dakota (adapted from Arndt, 1987).

Solution	Ca	Mg	Na	K	Alk	SO4	Cl	Tracer
	Concentration as mmol (p +/-)/L[1]							
Leaching	5.2	1.4	0.5	0.6	1.1	6.2	0.3	1.0
Porewater	30.9	28.4	12	1.8	11	60.8	1.3	0.0

1 Concentration is input as millimoles of charge (positive or negative) per liter of solution. Older literature may have these concentrations units as milliequivalents (meq) per liter solution.

Appendix A

Figures

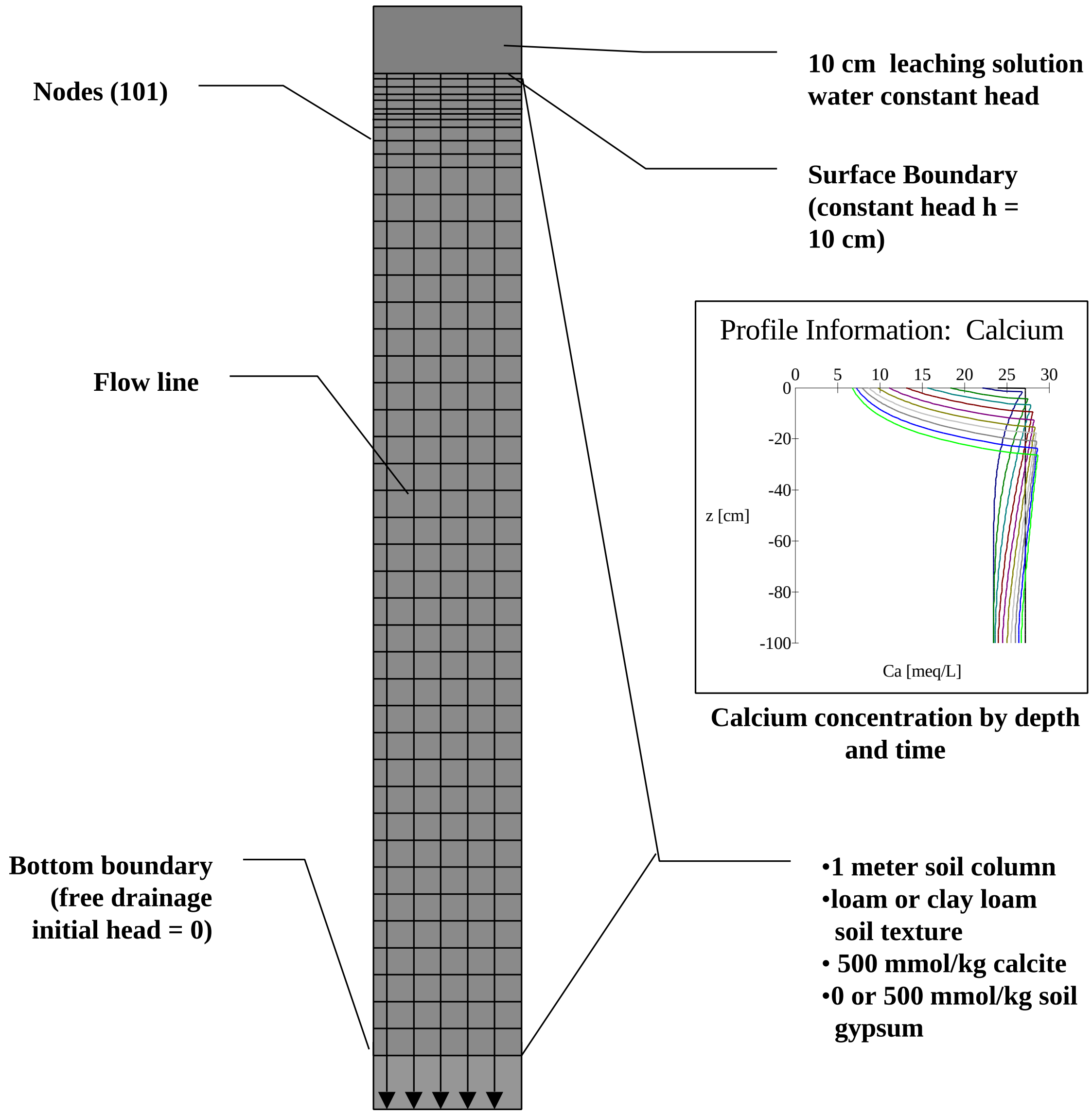
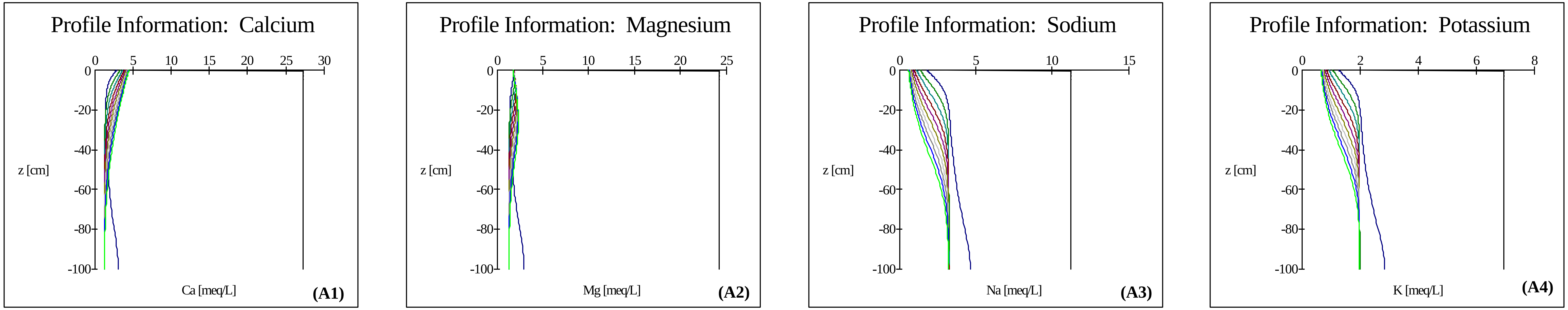


Figure 1. Selected physical and chemical features of the simulations. All conditions are held constant between the simulations with the exception of texture, texture related properties, and gypsum contents. Two groups of simulations were run, one on a loam soil and one on a clay loam soil. Two simulations were run within each soil texture group, one with gypsum and one without. Simulations were run for 10 days on loam and 100 days on clay loam in order to provide enough time to develop comparative patterns. Model output includes solute concentration by depth and time (exaple graph provided). Similar plots of solute concentrations by depth and time are interpreted in Figures 2 and 3.

A. Clay Loam Soils, No Gypsum, 500 mmol/kg Calcite, 100-day simulation



B. Clay Loam Soils, 500 mmol/kg Gypsum, 500 mmol/kg Calcite, 100-day simulation

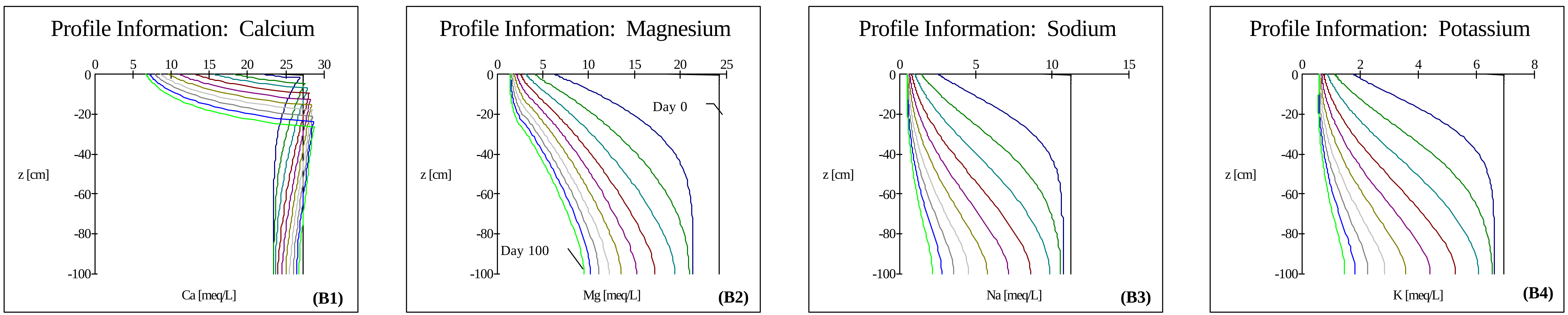
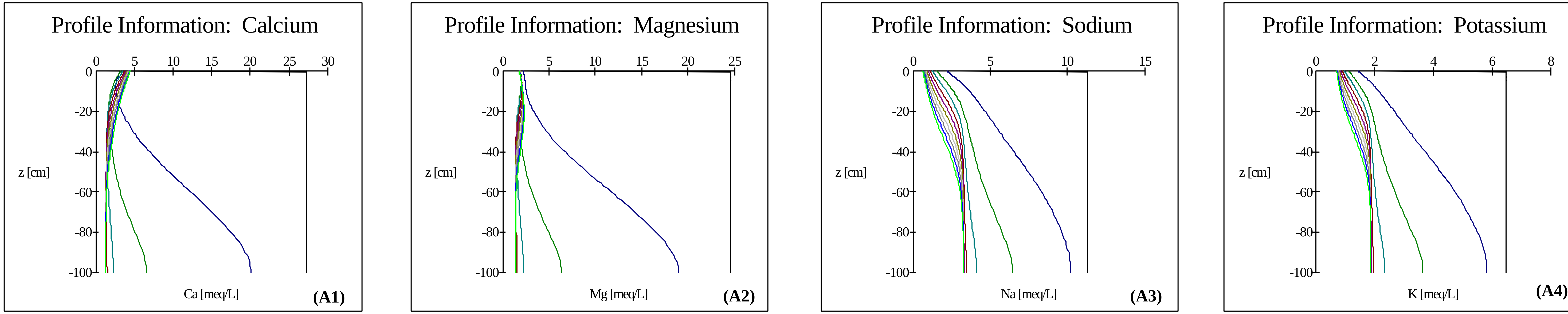


Figure 2. Pore-water solute concentrations plotted as a function of depth and time for fine-textured clay loam soils without gypsum and with gypsum (parts A and B, respectively). In each graph the vertical black line trace represents initial conditions at Day 0 of the simulation. The light green line trace generally found to the left indicates solute concentrations by depth at day 100. Lines in between represent concentrations in progressive 10-day intervals (see B2). Concentration units are in meq/L, which are equivalent to mmol(p+)/L. Saturated hydraulic conductivity of the clay loam soil was set at 6.24 cm/da.

Important features: (1) Ions in the concentrated pore-water solutions of the profiles without gypsum (A1-A4) are rapidly flushed from the soil column. (2) Pore-water solute concentrations are maintained at much higher levels in the profiles containing gypsum (B1-B4), in spite of the face that the same amount of water passes through both columns. Elevated solute concentrations are maintained because calcium released by gypsum dissolution is replacing adsorbed magnesium, sodium, and potassium. (3) Calcium concentrations are maintained at the solubility of gypsum until all gypsum is dissolved. Decreasing levels of calcium with time at the soil surface indicate when all gypsum in that zone has been dissolved (see B1).

Conclusions: As theory predicts, calcium released by gypsum dissolution acts to “mobilize” adsorbed magnesium, sodium, and potassium. Upon leaching, a greater quantity of salts more soluble than gypsum (e.g. magnesium and sodium sulfates) are released from a given weight of soil when gypsum is present than when gypsum is absent. The simulations indicate that the presence or absence of gypsum should be considered when modeling soil salinization processes in landscapes with gypsiferous, saline soils.

A. Loam Soils, No Gypsum, 500 mmol/kg Calcite, 10-day simulation



B. Loam Soils, 500 mmol/kg Gypsum, 500 mmol/kg Calcite, 10-day simulation

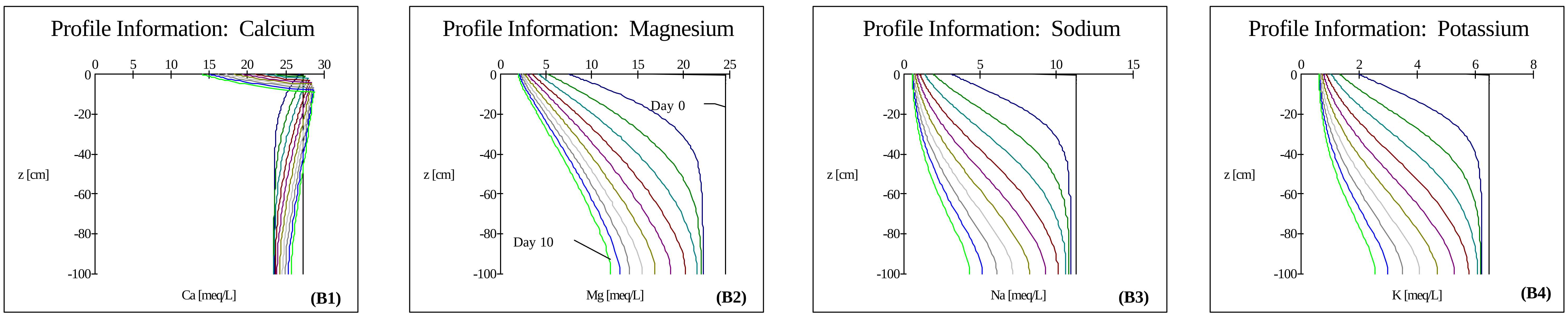


Figure 3. Pore-water solute concentrations plotted as a function of depth and time for medium-textured loam soils without and with gypsum (parts A and B, respectively). In each graph the vertical black line trace represents initial conditions at Day 0 of the simulation. The light green line trace generally found to the left of the graph indicates solute concentrations by depth at day 10 (see B2). Lines in between represent concentrations in progressive 1-day intervals (see B2). Concentration units are in meq/L, which are equivalent to mmol(p+)/L. Saturated hydraulic conductivity of the loam soil was set at 24.96 cm/da.

Important features: (1) The effects of gypsum dissolution on the mobilization of adsorbed cations in the loam soil are similar to those effects observed and discussed for the clay loam soil in Figure 2. (2) While the patterns are similar, the effects occur in approximately 1/10 of the time (10 days as opposed to 100). Two factors explain this result: 1) The greater hydraulic conductivity of the loam soil compared to the clay loam soil (24.96 opposed to 6. 24 cm/da, respectively) magnifies the intensity of leaching because a much greater amount of water moves through the soil for a given time period, and 2) the movement towards equilibrium between the leaching solution and cations adsorbed to soil particles is much faster in the loam soil because the soil cation exchange capacity is approximately half that of the clay loam soil (225 opposed to 450 mmol(p+)/kg soil, respectively).

Conclusions: The effects of gypsum increasing the salinization hazard of soils undergoing hydrologically induced salt mobilization are greater for fine textured soils when compared to coarse textured soils. However, the effects are mitigated to a large degree by the slower movement of water in the finer textured soils.

Appendix B

Appendix B

Description of Computer Models Used in the Analysis of Soil Salinization Processes

1. BACKGROUND

Computer models for solute transport and accumulation in variably saturated media can realistically and concisely illustrate salt movement processes in representative geohydrologic settings. Many existing computer models simulate solute transport in groundwater under saturated conditions. Fewer models address non-steady state solute-transport under variably saturated flow conditions, accounting for plant root withdrawals of water and temporal variations in precipitation and temperature. The computer models selected are user friendly, well documented and supported, and capable of well-defined graphical output for the purposes of visualization and economy in the presentation of results. It is not the purpose of the computer modeling effort to quantify soil salinization hazards associated with future conditions, but rather to support the identification of discrete areas that would have soil salinization hazards associated with the alternatives.

The United States Salinity Laboratory (USSL) in Riverside, California has a long history of developing computer models of solute transport in variably-saturated soils for the purposes of qualitatively illustrating salinization processes and quantifying salt distribution dynamics and secondary soil salinization hazards. Discussion with several USSL staff members has resulted in the selection of three USSL models that are readily available, applicable to both the scale and timing requirements of the Phase 2 Approach, and fully supported by developers, research groups, and internet user groups.

2. ROSETTA

Unsaturated hydraulic functions are key input data in numerical models of vadose (unsaturated) zone processes. These functions may be either measured directly or estimated indirectly through prediction from more easily measured data using quasi-empirical models. The unsaturated hydraulic properties used to drive the solute transport model use a variety of readily available, generic data appropriate for modeling representative but generalized geohydrologic settings. Data used to develop the unsaturated hydrologic functions are available from NRCS databases. Rosetta was developed to predict with increasing levels of accuracy the unsaturated hydraulic functions necessary to drive any model chosen to simulate solute transport in variably saturated sediments. Rosetta is included as a sub-routine in the HYDRUS 2D model selected to simulate salinization processes in representative geohydrological settings subject to the influence of the alternatives.

2.1. PROGRAM DESCRIPTION

The following text was taken from the model description provided by the NSSL and describes the program in detail. Further information can be found on the USSL web page.

< http://www.ussl.ars.usda.gov/models/rosetta/rosetta.HTM>

Rosetta V1.0 is a Windows 95/98 program used to estimate unsaturated hydraulic properties from surrogate soil data such as soil texture and bulk density. Models of this type are called pedotransfer functions (PTFs) since they translate basic soil data (such as those data found in the MUIR and SSURGO Databases) into hydraulic properties. Rosetta can be used to estimate the following properties:

- Water retention parameters according to van Genuchten (1980)
- Saturated hydraulic conductivity
- Unsaturated hydraulic conductivity parameters according to van Genuchten (1980) and Mualem (1976)

Rosetta offers five PTFs that allow prediction of the hydraulic properties with limited or more extended sets of input data. This hierarchical approach is of a great practical value because it permits optimal use of available input data. The models use the following hierarchical sequence of input data:

- Soil textural class
- Sand, silt and clay percentages
- Sand, silt and clay percentages and bulk density
- Sand, silt and clay percentages, bulk density and a water retention point at 330 cm (33 kPa).
- Sand, silt and clay percentages, bulk density and water retention points at 330 and 15000 cm (33 and 1500 kPa)

The first model is based on a lookup table that provides class average hydraulic parameters for each USDA soil textural class. The other four models are based on neural network analyses and provide more accurate predictions when more input variables are used. In addition to the hierarchical approach, Rosetta offers a model that allows prediction of the unsaturated hydraulic conductivity parameters from fitted van Genuchten (1980) retention parameters (Schaap and Leij, 1999). This model is also used in the hierarchical approach such that it automatically uses the predicted retention parameters as input, instead of measured (fitted) retention parameters. All estimated hydraulic parameters are accompanied by uncertainty estimates that permit an assessment of the reliability of Rosetta's predictions.

3. UNSATCHEM

Dr. Don Suarez of the United States Salinity Laboratory suggested the use of the UNSATCHEM program to determine whether the presence of gypsum would significantly influence the 2-dimensional modeling of salt transport in representative geohydrologic settings. The presence of gypsum may be a significant confounding factor because of the gypsum dissolution potentially providing a “constant source” of salinity ions. Solutes involved in soil salinity are partitioned into ions in solution and adsorbed ions. In fine-textured sediments, the solution chemistry of which is dominated by Na, Mg, and SO4, exchangeable cations represent a significant reservoir of soluble salts. As soluble ions move in response to altered groundwater flow patterns, gypsum dissolves and the released Ca ions exchange with adsorbed Na and Mg ions, providing an additional source of Na and Mg. The result is that the pattern of movement of soluble ions with time represents a constant-source/constant composition scenario as opposed to a simple "flushing" of soluble ions from one place to another. The effects may or may not be significant or not depending on texture, cation exchange capacity, and exchangeable cation composition.

The magnitude of gypsum's effect and its importance to specific settings were evaluated in column leaching simulations using UNSATCHEM. Appropriate physical and chemical soil data used for the simulations are available from the NRCS and North Dakota State University's soil science department.

In discussions with USSL staff, it was decided that potential gypsum effects would be evaluated with UNSATCHEM column simulations representing coarse, medium, and fine-textured soils assuming a constant weight percent of gypsum and a given concentration of saturation paste extract soluble ions representative of saline conditions. The effect of gypsum is to increase the length of time that salinization could occur and may not be significant over the time periods examined in the proposed Phase 2 modeling effort. It is possible that the presence or absence of gypsum would not greatly influence the results of HYDRUS 2D modeling. The presence of gypsum will only aggravate existing salinization hazards, not create new salinization hazards where none would exist in the absence of gypsum.

3.1. PROGRAM DESCRIPTION

The following text describes the program in detail. Further information can be found on the USSL web page.

<http://www.ussl.ars.usda.gov/MODELS/unsatchm.htm>

UNSATCHEM is a software package for simulating water, heat, carbon dioxide and solute movement in one-dimensional variably saturated media. The software consists of the UNSATCHEM (version 2.0) computer program, and the UNSATCH interactive graphics-based user interface. The UNSCHEM program numerically solves the Richards' equation for variably-saturated water flow and convection-dispersion type equations for heat, carbon dioxide and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The major variables of the chemical system are **Ca, Mg, Na, K, SO_4, Cl, NO_3, $H_4S_iO_4$, alkalinity, and CO_2**. The model accounts for equilibrium chemical reactions between these components such as complexation, cation exchange and precipitation-dissolution. For the precipitation-dissolution of calcite and dissolution of dolomite, either equilibrium or multi-component kinetic expressions are used which include both forward and back reactions. Other dissolution-precipitation reactions considered include gypsum, hydromagnesite, nesquehonite, and sepiolite. Since the ionic strength of soil solutions can vary considerably with time and space and often reach high values, both modified Debye-Huckel and Pitzer expressions were incorporated into the model as options to calculate single ion activities.

The program may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The flow region may be composed of nonuniform soils. Flow and transport can occur in the vertical, horizontal, or a generally inclined direction. The water flow part of the model can deal with prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, as well as free drainage boundary conditions. The governing flow and transport equations are solved numerically using finite differences and Galerkin-type linear finite element schemes, respectively.

4. HYDRUS 2D

The HYDRUS 2D program is a finite element model for simulating movement of water, heat, and multiple solutes in variably saturated media. The HYDRUS 2D model was developed by the USSL and is supported and provided by the International Ground Water Modeling Institute (IGWMC). The IGWMC distributes the program, is available to provide advice on specific modeling issues, and houses an active internet users group. The program has a windows interface, includes Rosetta (see Section 1 above) to parameterize unsaturated hydraulic soil characteristics, will handle estimates of plant root withdrawals of water, and models transient non-steady state conditions through time.

4.1. PROGRAM DESCRIPTION

The following text describes the program in detail. Further information can be found on the USSL web page.

<http://www.ussl.ars.usda.gov/MODELS/HYDRUS2D.HTM>

The HYDRUS 2D program numerically solves the Richards' equation for saturated/unsaturated water flow and the Fickian-based advection/dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The solute transport equations consider advective-dispersive transport in the liquid phase. The transport equations also include provisions for nonlinear and/or nonequilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero order production, and two first order degradation reactions: one which is independent of other solutes, and one which provides the coupling between solutes involved in sequential first-order decay reactions. The program may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media.

HYDRUS 2D can handle flow regions delineated by irregular boundaries. The flow region itself may be composed of nonuniform soils having an arbitrary degree of local anisotropy. Flow and transport can occur in the vertical plane, the horizontal plane, or in a three-dimensional region exhibiting radial symmetry about the vertical axis. The water flow part of the model can deal with (constant or time-varying) prescribed head and flux boundaries, as well as boundaries controlled by atmospheric conditions. Soil surface boundary conditions may change during the simulation from prescribed flux to prescribed head type conditions (and vice versa). The code can also handle a seepage face boundary through which water leaves the saturated part of the flow domain, and free drainage boundary conditions. Nodal drains are represented by a simple relationship derived from analog experiments.

For solute transport the code supports both (constant and varying) prescribed concentration (Dirichlet or first type) and concentration flux (Cauchy or third type) boundaries. The dispersion tensor includes a term reflecting the effects of molecular diffusion and tortuosity.

The unsaturated soil hydraulic properties are described using van Genuchten (1980), Brooks and Correy (1964) and modified van Genuchten type analytical functions. Modifications were made to improve the description of hydraulic properties near saturation. The HYDRUS2 code incorporates hysteresis by using the empirical model introduced by Scott et al. (1983) and Kool and Parker (1987). This model assumes that drying scanning curves are scaled from the main drying curve, and wetting scanning curves from the main wetting curve. HYDRUS2 also implements a scaling procedure (i.e. ROSETTA) to approximate hydraulic variability in a given soil profile by means of a set of linear scaling transformations which relate the individual soil hydraulic characteristics to those of a reference soil.

The governing equations are solved using a Galerkin type linear finite element method applied to a network of triangular elements. Integration in time is achieved using an implicit (backwards) finite difference scheme for both saturated and unsaturated conditions. The resulting equations are solved in an iterative fashion, by linearization and subsequent Gaussian elimination for banded matrices, a conjugate gradient method for symmetric matrices, or the ORTHOMIN method for asymmetric matrices. Additional measures are taken to improve solution efficiency in transient problems, including automatic time step adjustment and checking if the Courant and Peclet numbers do not exceed preset levels. The water content term is evaluated using the mass conservative method proposed by Celia et al. (1990). To minimize numerical oscillations upstream weighing is included as an option for solving the transport equation.

HYDRUS2 implements a Marquardt-Levenberg type parameter estimation technique for inverse estimation of selected soil hydraulic and/or solute transport and reaction parameters from measured transient or steady-state flow and/or transport data. The procedure permits several unknown parameters to be estimated from observed water contents, pressure heads, concentrations, and/or instantaneous or cumulative boundary fluxes (e.g., infiltration or outflow data). Additional retention or hydraulic conductivity data, as well as a penalty function for constraining the optimized parameters to remain in some feasible region (Bayesian estimation), can be optionally included in the parameter estimation procedure.

The Microsoft Windows based Graphical User Interface (GUI) manages inputs required to run HYDRUS 2D, as well as grid design and editing, parameter allocation, problem execution, and visualization of results. The program includes a set of controls that allows the user to build a flow and transport model and perform graphical analyses on the fly. Both input and output can be examined using areal or cross-sectional views, and line graphs. The HYDRUS 2D shell program translates all geometric and parameter data into the required format. File management is handled by a sophisticated project manager.

Data preprocessing involves specification of the flow region having an arbitrary continuous shape bounded by polylines, arcs and splines, discretization of domain boundaries, and subsequent generation of an unstructured finite element mesh. HYDRUS 2D comes with an optional mesh generation program MESHGEN-2D by PC-Progress. This program, based on Delaunay triangulation, is seamlessly integrated in the HYDRUS 2D environment. In the absence of the MESHGEN-2D program, the HYDRUS 2D shell provides an option for automatic construction of simple, structured grids.

Output graphics include 2D contours (isolines or color spectra) in areal or cross-sectional view for heads, water contents, velocities, and concentrations. Output also includes velocity vector plots, animation of graphic displays for sequential time-steps, and line-graphs for selected boundary or internal sections, and for variable-versus-time plots. Areas of interest can be zoomed into, and vertical scale can be enlarged for cross-sectional views. The mesh can be displayed with boundaries, and numbering of triangles, edges and points. Observation points can be added anywhere in the grid. Viewing of grid and/or spatially distributed results (pressure head, water content, velocity, or concentration) is facilitated using high resolution color or gray scales. Extensive context-sensitive, online Help is part of the interface.

5. GENERAL COMMENTS ON COMPUTER MODELING ASSUMPTIONS

The proposed models were selected based on the suggestions of several experts in the field and are applicable to the intended use. It was found during model parameterization that the inclusion of time variable parameters such as daily precipitation and evapotranspiration values in models of complex landscape settings of large extent resulted in excessively long model runs and numerous model failures where the model did not converge on a useable value. The development of a detailed model that accounts for daily climatic variations and uses actual field data for the parametrization of hydraulic characteristics was beyond the scope of this study. Therefore several simplifications were introduced into the model under the advice of NSSL staff, including.

1. Precipitation was indirectly introduced into the models by developing a net evapotranspiration balance that reflects a precipitation deficit representative of the portions of the northern plains that are the subject of the study.
2. The salinity output conditions of the initial model run were used as input for successive runs, with the exception that initial head distribution values reflective of spring conditions were used for each yearly simulation. This simplification results in a homogeneity of climate that would represent the long-term climate. However, the resulting simulations do not reflect transient events such as long-term drought and pluvial conditions or short term, high intensity precipitation events that can have an effect on the movement of salts in the soil.
3. Default saturated and unsaturated hydraulic characteristics were used that were representative of the textural class of the applicable material. The output of the resulting simulations would likely differ slightly if more detailed data obtained from laboratory analyses providing moisture characteristic curves, bulk density, and saturated and unsaturated hydraulic conductivity were available.
4. Salinity was modeled as a conservative (non-reactive) single constituent that would generally reflect electrical conductivity (as mmol/cm) or total dissolved solids. This assumption is fairly realistic; however, deviations from the simulated predictions result from calcite precipitation and gypsum dissolution, resulting changes in the composition of the cation exchange capacity mobilizing adsorbed cations.

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